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URANIUM ARC FISSION REACTOR FOR SPACE POWER AND PROPULSION

submitted by

Richard T. Schneider
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Final Report for SBIR Contract NAS-26318

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PROJECT SUMMARY

Combining the proven technology of solid core reactors with uranium arc confinement and non-equilibrium dissociation and ionization by fission fragments can lead to an attractive power and propulsion system. The benefit ensues from using the high quality directed energy of fission fragments and associated radiation to obtain working fluid/propellant dissociation and ionization directly, without first degrading the energy to heat. The dissociation and ionization energies can be utilized in a nozzle, thruster or MHD accelerator/generator.

Uranium arc technology is being developed for use in space nuclear thermal and electric propulsion reactors. In the Uranium Arc Fission Reactor, arcs are driven mainly by fission energy and require little electrical energy input. The arcs operate at 10,000 K, and transfer energy to the propellant or working fluid via optical radiation, thus avoiding material temperature limitations. The result is a propulsion afterburner that can elevate fluid temperatures to levels above the melting point of any material (above 4,000 K). This enables very high specific impulse propulsion or ultrahigh temperature power conversion.

Fission events in the nuclear arc plasma provide for additional dissociation and ionization of propellant or working fluid via fission fragments and ionizing radiation. This ionization, plus associated enhanced fluid properties such as electrical conductivity, lead to a reduction in the electrical energy that must be invested to dissociate and ionize the propellant in an electric thruster (MPD-arc) or MHD generator. For space power platforms, the resultant reduced electrical power input requirement provides for improved efficiency, reduced and easier waste heat rejection and thus a more compact, lower mass reactor design.

An experimental program was conducted to shown that fission energy can be used to increase the temperature of an arc plasma, and thus increase the radiative energy transfer from the arc. Helium vortex stabilized arcs of uranium and boron were operated in a thermal neutron flux of 10^6 n/cm^2 sec. The intensities of observed spectral lines increased during irradiation. The spectroscopically measured temperature increased from 8,100 K to 9,400 K (15%) for uranium arcs, and from 9,500 K to 11,500 K (20%) for boron arcs. This effect is attributed to the more efficient ionization mechanism of high energy charged particles compared to electric field/ohmic heating.

Additional experiments were performed to demonstrate that the radiative energy could be absorbed in an external propellant or working fluid. The experiments showed that 90% of the emitted light was absorbed at a particle density of 2×10^{19} cm^{-3} (1 atm and 360 K) and an optical path length of 10 cm. Subsequent experiments showed that the uranium loss rates during arc operation could be reduced to a few mg/cm^{2}s by proper electrode design.

The experimental results indicate the fundamental feasibility of uranium arc driven energy transfer. For thermal propulsion, increased temperatures mean higher specific impulse. For space power platforms, the resultant improved efficiency means reduced and easier waste heat rejection and thus a more compact, lower mass reactor design. A more efficient thruster also results in lower power requirements or reduced radiator area and thus mass. The technology is also applicable for more efficient and safer ground-based electric power generation. A spinoff development is the technology for handling uranium and its compounds in liquid and vapor forms. This technology will be required in advanced Gas and Vapor Core Reactors.

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1. INTRODUCTION

1.1 Identification and Significance of the Problem or Opportunity.

Power and propulsion systems utilizing nuclear fission energy possess many advantages over chemical propulsion systems. These include:

- o Higher achievable operating temperatures
- o Much greater energy and power densities
- o Efficient non-thermal ionization mechanisms

These advantages lead to significant mission performance advantages over chemical systems. However, in spite of these advantages, systems using nuclear reactors are still performance limited by the constraints imposed by material temperature limits and heat transfer via standard thermal processes. In this work, we seek to overcome these limitations by

- o using radiative energy transfer mechanisms to avoid material temperature limitations and enhance heat extraction, and
- o exploiting the high quality ionization of fission fragments to increase efficiency.

To achieve fission's performance potential, many space nuclear power and propulsion systems based on solid- and gaseous-core reactors have been extensively studied during the past 40 years. The limitations on the performance of these systems, whether specific impulse, thrust-to-weight ratio, or specific mass, are imposed by the maximum effective temperature available for energy transfer, energy conversion and heat rejection. For solid fueled reactors, these limits are dictated by the fuel melting temperatures and associated cycle materials temperatures. With these constraints, solid core reactor-based propulsion systems still yield specific impulses of up to 1000 to 1200 seconds, over twice the specific impulse of chemical propulsion systems producing comparable thrust.

Presently, the most promising approach to overcoming these inherent limitations is to use a fissile fuel in vapor, gaseous or micron-size liquid droplet phase in the core at thousands of degrees K hotter than the materials containing the system. The conversion and thermal management system, coupled to the ultrahigh temperature reactor, have to provide efficient energy conversion while still maintaining heat rejection temperature in the 1600 to 2100 K range. With these constraints, a gaseous core reactor's specific mass can be as low as ~1 kg/kW, and the specific impulse can be as high as 3,000 to 5,000 seconds due to the high working gas or propellant temperature at high pressure.

The major problems with gaseous core reactors are confinement of the fuel in the core region while simultaneously achieving the requisite high temperature energy transfer from the fuel to the working fluid or propellant. In this work, we propose a new reactor concept which overcomes these problems by taking advantage of electric field confinement of the fuel gas -- the Uranium Arc Fission Reactor (UAFR).

Energy transport processes in a fissioning plasma could enable ultrahigh temperature power conversion or very high specific impulse propulsion. Energy transfer from the fissioning fuel to the working fluid used in the power conversion system or propellant in the case of propulsion is accomplished by dissociating and ionizing both the fuel and the working fluid in and close to the plasma region. The highly efficient ionization source of the fission fragments can be used to couple energy directly into the arc. This is combined with radiative coupling of the ionized working fluid with the bulk working fluid flowing external to the arc to achieve efficient energy transfer. The working fluid can then be used for open cycle direct thrust, or in closed cycle energy conversion.

The performance of this new system lies between those of the solid and gaseous core systems in terms of specific impulse. An embodiment of the UAFR concept is discussed in Section 2. In such a reactor the majority of the nuclear fuel is in the form of solid material or a molten uranium metal pool. However, a minority amount of the nuclear fuel is in the form of an arc plasma (~8000 K) emanating from the molten uranium pool. Containment of this plasma is provided by the electromagnetic forces of an arc. Since melting of the pool and ionization of the arc is provided by nuclear fission, the required electrical power input is minimal.

A significant advantage of this approach is that the bulk of the ultrahigh temperature nuclear fuel does not circulate and is thus contained in the core (solid or otherwise) without requiring hydrodynamic containment. Achievement of criticality is therefore no longer linked to the operating pressure. Dissociation and ionization are achieved by interactions with the fission fragments and associated radiation. Radiation transfer occurs at photonic speed without having to cross material surfaces, as opposed to conventional heat transfer which occurs at phononic speed (speed of sound) and requires heat transfer surfaces.

The efficient ionization caused by fission fragments can also be applied to advantage in a new thruster concept -- the nuclear-augmented thruster. Previous neutron irradiation experiments performed by us at Los Alamos National Laboratory's Godiva reactor have shown that fission fragment ionization can be used to increase the conductivity of a plasma by factors of greater than ten over its thermal equilibrium level.[1,2] In the present concept, the electrical energy normally supplied to an MPD thruster to ionize the propellant before acceleration and exhaust is replaced by more efficient direct fission fragment ionization. This leads to significantly reduced electrical energy input requirements. Reduced electrical needs translate into lower reactor power generation requirements, less heat rejection area and thus lower overall system mass.

1.2 Phase I Technical Objectives

The research described herein is directed to the demonstration of the scientific feasibility and technology development of the key aspects of non-thermal mechanisms of energy transfer, dissociation, and ionization via fissioning arcs.

The objectives of the experiments described here were to demonstrate that fission energy can be coupled to the ionization and radiative emission of the arc, that the enhanced arc emission can subsequently be radiatively coupled to a working fluid or propellant, and that this augmented heat transfer occurs without significant loss of the nuclear fuel. Nuclear effects caused by fission fragment and gamma irradiation were obtained both directly by using uranium, and simulated by using the charged fission fragments from the $^{10}B(n,^{4}He)^{7}Li$ nuclear reaction.

In a conventional arc, electrical energy is converted into heat via ohmic heating and collision-dominated mechanisms. A nuclear-augmented uranium arc derives most of its power directly from the fission energy of the fuel and requires little electrical energy input. Such a uranium arc operates at 10,000 K, and transfers its energy to the propellant or working fluid via optical radiation, in addition to the conventional heat conduction and convection. The result is similar to a propulsion afterburner that can elevate fluid temperatures to levels above the melting point of any material (above 4000 K) since energy transfer occurs without crossing solid material boundaries. This enables very high specific impulse propulsion,[2,3] ultrahigh temperature power conversion, or more efficient thruster designs.

In a conventional electrical arc, most of the energy provided by the power supply is used to ionize the participating arc species. After this latent heat has been provided, additional energy is then spent in heating the plasma. Depending on the arc design, some energy is also required to provide the latent heat necessary to evaporate atoms from the solid interface of the electrodes. In this report we explore an alternate method of providing ionization to the arc. Ionization can be achieved by exposing the arc to an external source, such as an electron beam, or by using a fissile plasma in a neutron environment. In the latter, fission events at or near the electrode surface provide for latent heat, dissociation and ionization of plasma species via fission fragments and ionizing radiation. This results in direct energy input into the arc via electron collisions with the arc plasma. An additional energy source is the fissioning that occurs directly in the plasma column.

In our experiments we augment a conventional electrical arc with a fissile component. As the fissile plasma is exposed to neutrons, fission occurs and a new source of ionization is created. The electrical power that was previously used to ionize is now available for other purposes, provided that the electrical power input is held constant (i.e., via a constant current power supply). In such an arc, this newly available power provides additional ohmic heating of the plasma, thereby increasing its overall temperature and radiative emission. The experimental verification of this effect is reported here. In addition, we demonstrate that the radiated energy can be absorbed by a second medium, and that the process occurs without significant loss of the fissioning material.

2. URANIUM ARC FISSION REACTOR AND NUCLEAR-AUGMENTED THRUSTER CONCEPTS

2.1 Physics Basis

The high power capabilities and compactness of nuclear reactors offer the potential for extremely high power densities. However, even though the energy output per uranium fission event of 200 MeV is 10^8 times the typical 1 eV output of chemical systems, the state-of-the-art in nuclear energy conversion has not advanced beyond degradation of the released fission fragment energy to heat. The maximum temperature of this conversion process is thus constrained by material limits. The net result is that nuclear power has been energy extraction limited, and has not even nearly approached its generation limit. To take advantage of this characteristic of high power density, nuclear power could thus most benefit from the use of advanced power extraction mechanisms.

In a traditional heat engine, the dominant heat extraction mechanisms are heat conduction and convection, with usually minor contributions from radiative heat transfer. However, heat conduction and convection are accomplished by phonon transfer at the speed of sound of the material, while radiative transfer is accomplished by photons moving at the speed of light. Thus, if fast energy extraction as desired with fissioning sources, radiative heat transfer is preferred. This conclusion was readily understood by the early proponents of Gas Core Reactors, e.g., the Nuclear Light Bulb Engine.

In addition to radiative heat transfer, there are additional heat transfer mechanisms that could be used for rapid heat transfer. When hot gases intermix at different temperatures, e.g., a fissioning gas in an arc plasma, energy interchange occurs not via phonon interactions, e.g., lattice vibrations, but by collisions such as atom-atom and electron-ion, which may include recombination and re-emission of radiation. Collision frequencies in high temperature gases and plasmas are relatively high, and therefore the energy transfer rate is correspondingly high. The high ionization rates in a fissioning plasma make these modes of heat transfer very efficient.

In addition to the limitations on heat extraction, traditional heat source performance is limited by the tradeoff between Carnot efficiency and waste heat rejection area. In the environment of space, heat rejection is accomplished via radiation. Since efficiency, given a specified material-limited source temperature, is inversely proportional to the first power of the heat rejection temperature, whereas heat rejection area (mass) varies inversely with the fourth power of the heat rejection area, minimum mass in orbit for traditional heat sources is achieved by maximizing the heat rejection temperature and accepting lower efficiencies. By rejecting heat at highest temperature, nuclear reactors offer a conceptually straightforward method for minimizing radiator mass. However, the mechanisms proposed herein for radiative and collisional energy transfer without crossing material surfaces then offer the potential for the highest source temperature, thus maximizing efficiency, <u>plus</u> the potential for the highest heat rejection temperatures, minimizing radiator mass.

Finally, the efficient ionization caused by fission fragments can be used for more than just to enable fast collisional energy transfer. It can be used to reduce electrical energy requirements of electric propulsion engines. In such engines, the majority of the electrical energy input is used to ionize the propellant. A smaller portion of the electrical energy is then used to elevate the plasma temperature before exhaust.

Ionization of the propellant is caused primarily by atom collisions with electrons whose energies are above the propellant's ionization energy. The number density of these electrons in the tail of the Maxwellian distribution of the plasma electrons is relatively low -- less than 1% of the bulk electron number density. The electrical energy requirement for ionization is high because each ionization event requires eV's per atom, e.g., 5.4 eV for lithium or 8.3 eV for boron, and because the electrical energy transfer process must heat the entire electron population distribution in order to populate the high energy electron tail of the Maxwellian distribution of the plasma electrons.

Direct fission fragment ionization, however, provides large numbers of high energy electrons of energies above the ionization potential of all atoms. For a plasma at 4000 K, the number density of these electrons has been estimated at 10^3 to 10^4 times higher than the corresponding number density in the Maxwellian distribution.[5] This is equivalent to the population density of a 10,000 K plasma. In other words, a 4000 K fissioning plasma provides the ionization equivalent of a thermal plasma at 10,000 K.

The gain in efficiency comes from replacing the electrical energy that would otherwise had to have been provided to heat the plasma to the higher temperatures. The decrease in electrical energy input further results in a decrease in the thermal energy to be rejected and a corresponding decrease in the size and mass of the space radiators.

The neutron capture reactions available with which to enable the above features include the following:

$^{3}He(n,p)T$	765 keV
$^{6}Li(n,T)^{4}He$	4.8 MeV
$^{10}B(n,^{4}He)^{7}Li$	2.8 MeV
$^{235}U(n,ff)ff$	200 MeV

The uranium fission reaction listed is representative of that possible with other fissionable isotopes, e.g., ^{233}U.

2.2 Uranium Arc Fission Reactor Concept Description

The UAFR bridges the gap between solid core nuclear reactors and gas core reactors. It further relaxes the high materials temperature limitations of solid core reactors and allows contact of ultrahigh temperature propellant with materials that are non-nuclear, not mechanically stressed, and have high utilization temperature, e.g., tungsten and graphite, or are actively cooled, such as the nozzle. It also minimizes the radiative heat transfer and mass loss problems of gas core reactors by using electric arc confinement of the fuel, radiative and collisional processes for rapid energy transfer at ultrahigh temperatures without crossing material surfaces, and direct ionization to minimize the electrical energy requirements.

A schematic diagram of the reactor is shown in Figure 1. The figure shows a reactor very similar to the typical NERVA-type solid core, with the addition of a fissioning arc section at the aft end of the core. Propellant is first heated in the solid core in the conventional manner. Then, instead of discharging into the exhaust chamber before entering the nozzle, the propellant is heated to ultrahigh temperatures in the uranium arc region.

An individual arc element is shown in Figure 2. The uranium fuel is contained in a tungsten tube that serves as one of the electrodes in the arc circuit. The tube is cooled by graphite fins in contact with the propellant. A uranium arc is established between the liquid uranium surface (meniscus) and a tungsten or graphite electrode pin. (The radiation standard for optical radiation measurements operates a graphite pin at 4000°C.) The uranium arc operates at 8,000 K to 10,000 K. An end view of the array of arc elements at the aft of the reactor is shown in Figure 3. The diamond shaped spaces formed by connecting the cooling fins serve as flow channels for the propellant.

The nuclear-augmented electric arc serves to heat the propellant and deter uranium loss. The heat transfer mechanism from the arc plasma to the propellant is via radiative transfer. In a conventional arc, the electrical input to the electrodes is used to heat the electrodes, ionization, and elevating the temperature of the working fluid. Electrode heating and ionization constitute the bulk of the input energy requirements, yet do not lead to increased plasma temperature. After these two requirements have been satisfied, additional energy, the smallest fraction of the three, is then used to increase the plasma temperature and converted exclusively into radiation which can be transferred to a second medium. However, electric field/ohmic heating by itself is a very inefficient way to heat the plasma.

In the nuclear-augmented uranium arc, the energy required for heating the electrodes and for ionizing (several eV) at the uranium surface and in the arc, are provided directly by fission fragments. This displaces the portion of electrical energy that does not lead directly to higher plasma temperature. Thus nearly all electrical energy input, plus the fission energy released in the plasma column, are used to heat the plasma column to arc temperatures, typically ~1 eV. Furthermore, this energy is reemitted as radiation and can be used to heat the propellant without crossing solid material surfaces. The absorption of energy by a seeded propellant was experimentally demonstrated and reported in References 3 and 6.

Older gas core concepts relied on radiative transfer assuming a uranium plasma emitting blackbody radiation. This was required by the need to transfer all the reactor power in this manner, and the assumption that only the fourth power dependence of blackbody radiation on temperature could accomplish this. This may have been true at the operating pressures previously proposed for these devices, e.g., 500 atm. A plasma will indeed appear as a blackbody radiator

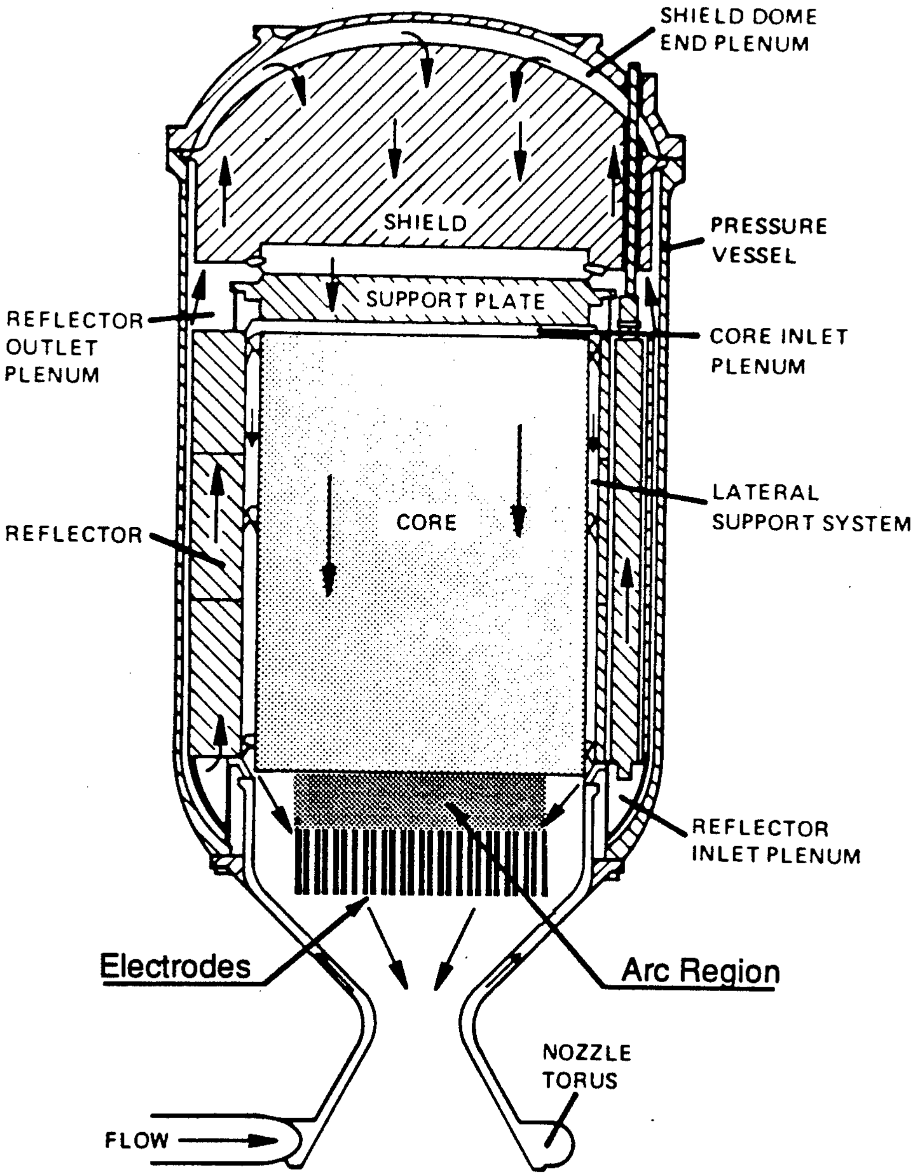

Figure 1. Uranium Arc Fission Reactor (UAFR) Schematic

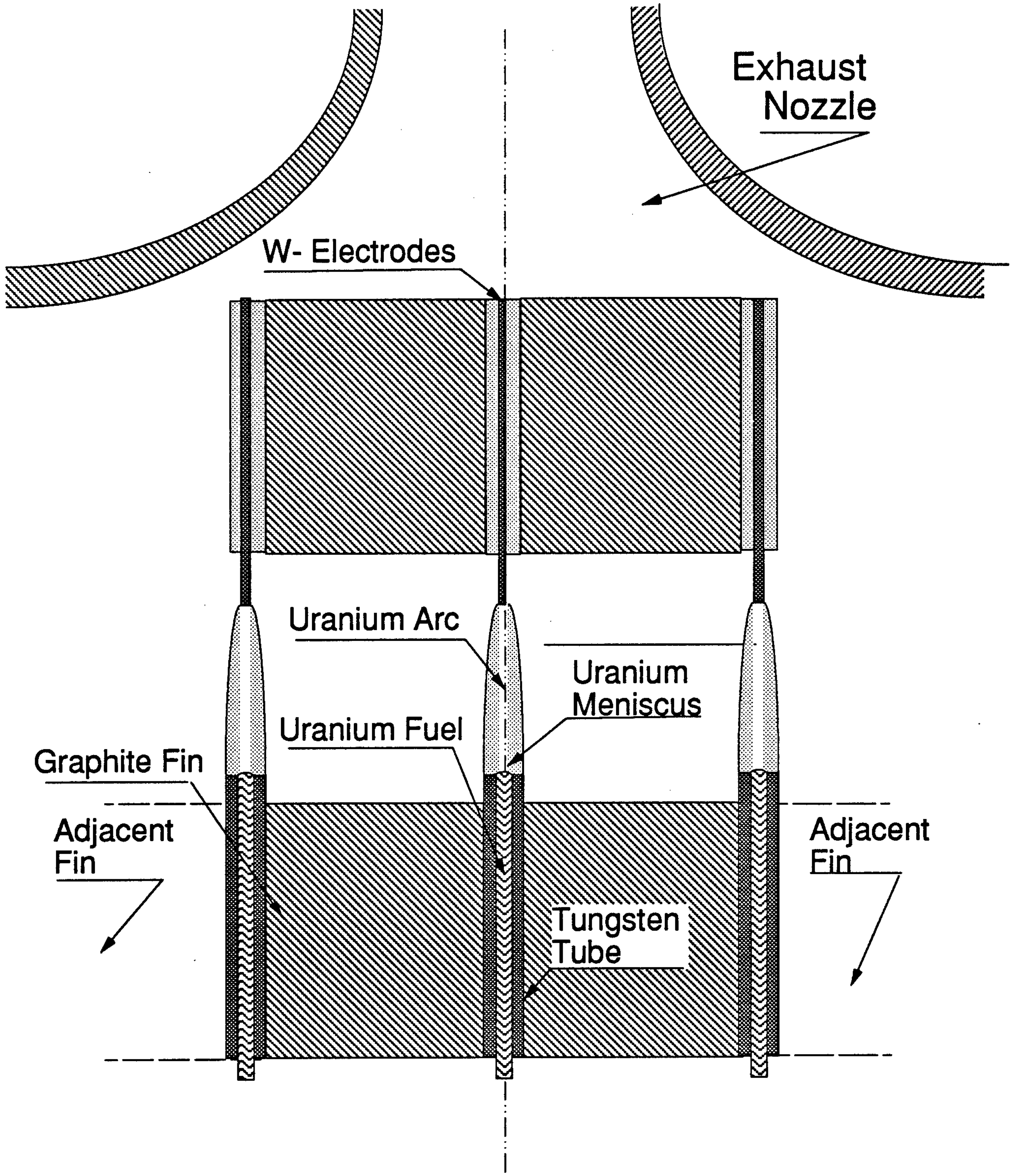

Figure 2. Fuel Elements in Arc Region

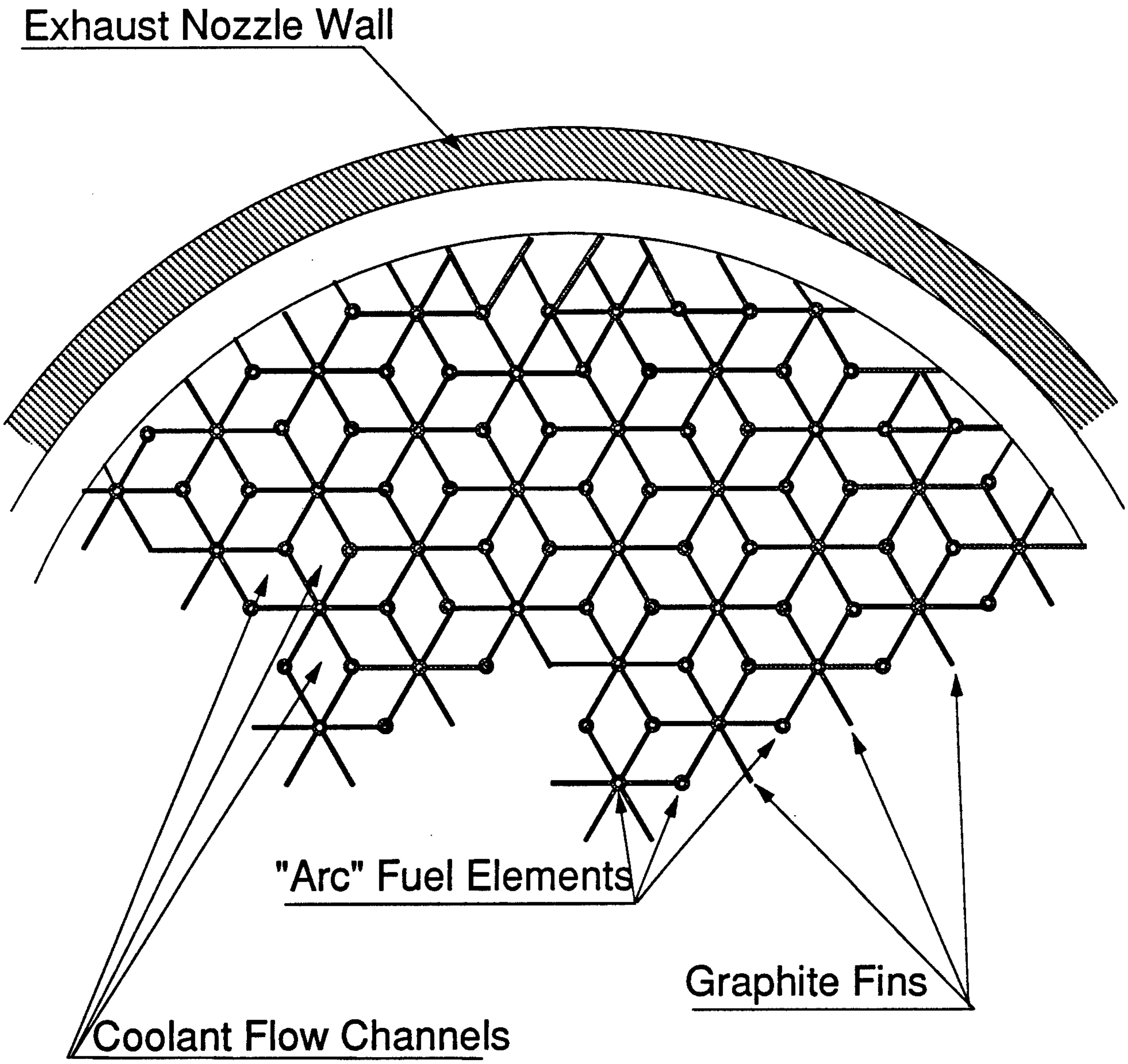

Figure 3. Fuel-Arc Element Array at Reactor Aft.

at these pressures. However, at the uranium pressures currently projected in the arc region, i.e., 25 to 50 atm, the plasma will be a line radiator. In a conventional electric arc, local thermodynamic equilibrium (LTE) can be assumed, and the line radiation power density is a function of the plasma temperature and density of the radiating particles. The nuclear-augmented arc may provide for additional nonequilibrium radiation, i.e., non-thermal radiation in that the radiation density is not due to a temperature effect. This uranium line radiation can be absorbed by the seeded propellant.

2.3 Nuclear-Augmented Thruster Concept

The ionization caused by fission fragments can be used to increase the efficiency of electric thrusters. Typically, these devices use a large fraction of their electrical energy input to ionize the propellant before exhaust. The fractions range from ~10% to 15% for lithium propellant (ionization potential 5.4 eV) to ~30% to 45% for argon (ionization potential 15.8 eV). The required energy and ionization can be efficiently provided by fission fragments.

This can be accomplished by locating the thruster in close proximity to the nuclear reactor. Then, by seeding the thruster propellant with the materials listed above, e.g., ^{6}Li, ^{10}B, etc., neutrons escaping from the reactor core can be captured to provide the ionization of the propellant directly. If the propellant is lithium, the propellant serves both purposes of thrust and ionization enhancement via the ^{6}Li(n,T)^{4}He neutron capture reaction. Lithium is a solid at earth room temperature, and thus does not require a refrigeration system. It also minimizes the required cargo space. In addition, mission safety concerns of gas leakage are minimized, and operational reliability is increased by avoiding the refrigeration unit.

In addition to providing the ionization of the propellant, fission fragments will increase the conductivity of the plasma as described in References 1, 2 and 5. Fission fragments born at high energy (100's of keV to MeV) transfer their energy to electrons during slowing down. As these electrons then slow down via collisions, there will be an increase in the population of electrons capable of ionizing the plasma. The fissioning plasma will be ionized to a degree corresponding to those of plasmas at much higher thermal temperatures. In effect, this decreases the temperature to which the propellant needs to be heated to achieve the necessary acceleration. The net result of the "free" ionization provided by neutrons that would have normally escaped, and the enhanced conductivity of the plasma is to significantly increase thruster performance efficiencies.

2. EXPERIMENTAL SET UP

The fission reaction in the initial experiments was simulated with the ^{10}B(n,alpha)^{7}Li reaction. Experiments were performed to observe the effect of the neutron flux on the boron 249.7 nm doublet. To accomplish this, the cathode pin was filled with boron and the emission spectra of the arc were observed. Subsequent experiments were performed with uranium, and the uranium atom (U I) lines at 365.3 nm and 365.9 nm, and uranium ion (U II) line at 417.1 nm were observed.

A helium vortex-stabilized arc was used in the study. A schematic view of the assembly is shown in Figure 4. Helium is injected at an angle through the bottom plate of the assembly, and exit through the top into a catch tank. The cathode pin is made of carbon due to its inherent stability in arc formation. A bored hole in the center allows for the introduction of boron or uranium during the arc. The bottom plate through which the cathode emerges is internally water-cooled. A tungsten anode is attached to the internally water-cooled copper back plate. The arc section is enclosed by a cylindrical quartz envelope, and the overall total length of the arc chamber is 0.1 m.

Spectroscopic analysis was achieved by setting up an incoherent fiber optic waveguide which would transport optical information from the arc to a spectrometer located in the control room 60 feet away. The waveguide consisted of 64 quartz fibers of 100 micrometer in diameter. Attenuation in the waveguide is wavelength dependent and calibrations were performed using tungsten ribbon calibration standards. The middle of the arc plasma was focused on the fiber optic bundle.

A Czerny-Turner type spectrometer with an overall focal length of 48 inches was used for spectrometric analysis. The grating used was 1190 grooves per millimeter with a blazing wavelength of 500 nm. The linear dispersion was measured to be 0.644 nm per millimeter spread. The entrance slit of the spectrometer was set at 20 micrometers. The spectrometer could be run both in multiline or monochromator mode. In the multiline mode, a series of waveguides were positioned at the exit plane to detect two or more predetermined spectral lines. In both observation modes, each line was detected by a photo-multiplier tube (PMT) (Hammamatsu Model R376) and photocurrent signals were transformed into voltage signals using preamplifiers (Hammamatsu Model C1053).

The experiments were performed at the Plasma Irradiation Facility using the Kaman A-711 Neutron Generator. The Kaman A-711 generates neutrons by means of the DT reaction which produces 14.7 Mev neutrons. Proper moderation is used to thermalize the spectrum, resulting in a fast to thermal neutron ratio of 1:10. The thermal neutron flux was measured to be $10^6/cm^2$ sec.

The operating procedure was as follows. A neutron flux was established in the test section. The arc was then initiated remotely and boron emission line intensity data were recorded for about 30 to 40 seconds. The neutron source was then shut down while the arc continued operation, and data were recorded for another 30 seconds. The neutron source was then instantly brought back to the initial flux value, and data recorded an additional 30 seconds. The arc voltage and current conditions were maintained constant throughout the experiment. Line emission intensities were measured with photo-multiplier tubes at the exit slits of the spectrometer in the control room.

Experiments were also performed with uranium arcs to measure the energy transfer from the arc to uranium hexafluoride gas in an absorption cell. A power radiometer sensitive to the

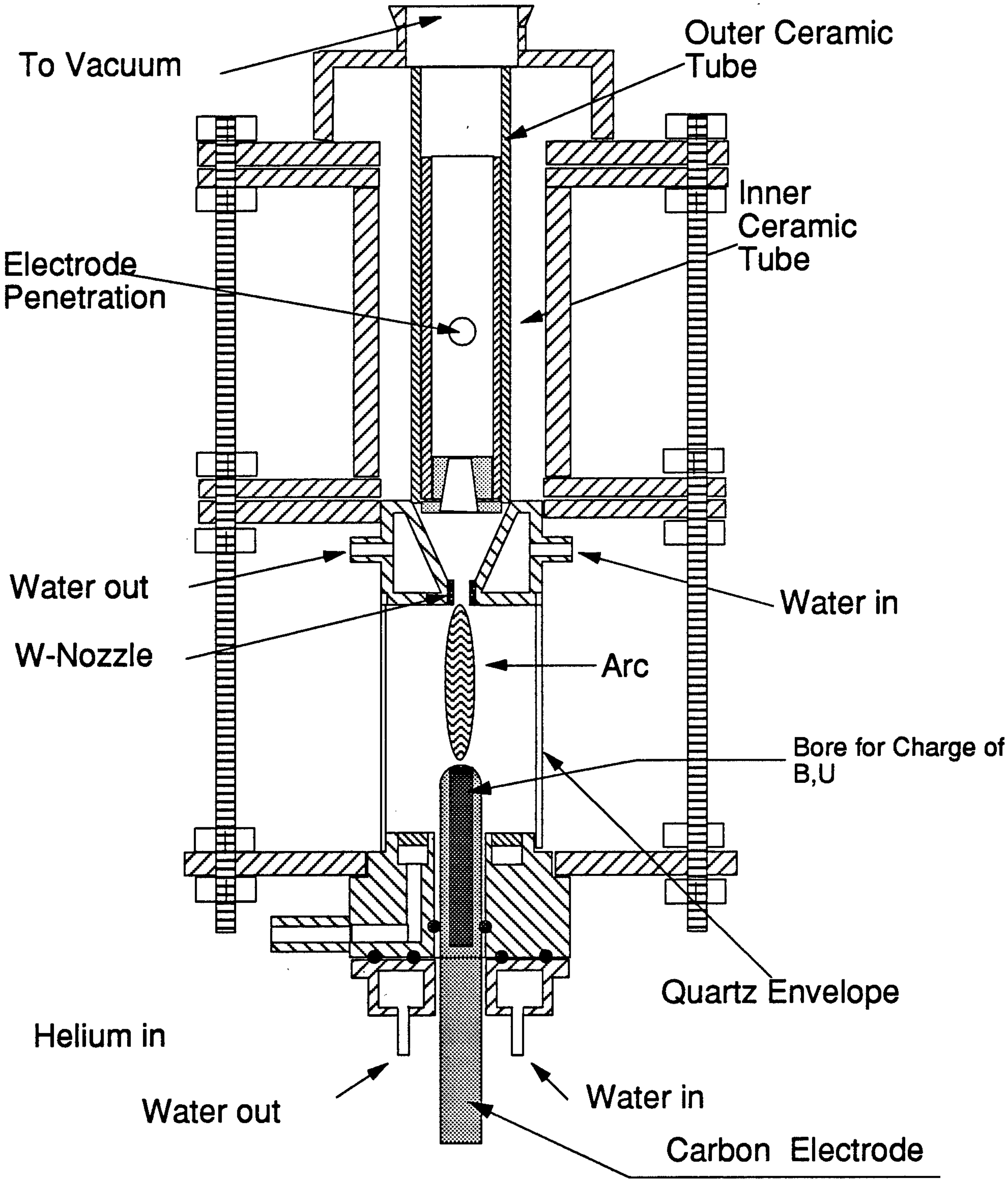

Figure 4. Schematic Diagram of Vortex Stabilized Arc

full spectrum of emitted light was arranged to detect the total light intensity transmitted through the absorption cell.

The final aspect of feasibility examined in the current effort was containment of the uranium. For these measurements, the cathode pin was loaded with a measured quantity of uranium. A uranium arc with a helium vortex gas flow was operated for a specified period of time. The uranium remaining in the pin was weighed, and the uranium mass transfer out of the arc was determined.

4. RESULTS AND DISCUSSION

4.1 Spectral Line Emission Intensity

The emission spectra of boron, carbon, helium and uranium were measured to establish the baseline conditions. These are shown in Figures 5a through 5d. From the measured spectra, candidate emission lines were selected on which to observe the influence of neutron irradiation.

An initial series of boron seeded helium arc experiments were performed to determine the effect of neutron irradiation. The spectrometer was arranged to detect in a monochromator mode. The 249.7 nm boron doublet line intensities as a function of neutron irradiation are shown in Figure 6. Neutron irradiation is performed during the early sequence, irradiation is stopped during the middle sequence, and irradiation is again performed during the last part of the sequence. The figure clearly shows a two-fold increase in the line intensity when the neutron source is on, both during the initial and final irradiations. This effect was observed repeatedly under various arc current-voltage conditions. The effect was also observed for the adjacent 247.9 nm carbon line emitted by vaporized cathode material, as shown in Figure 7.

The increased line emission intensity is interpreted as an increase in the arc temperature made possible by a more efficient ionization mechanism provided by the high energy nuclear reaction products. The constant-current power supply continues to supply the same power to the arc during irradiation, as shown in Figure 8.

4.2 Plasma Temperature Measurements

The temperature of the arc with and without irradiation was obtained from helium line ratio measurements. The technique used is the relative line intensity temperature method [7-9]. The technique is based on the measurement of line intensities and their ratio gives the temperature according to the following relationship:

$$I_i = n_0 \, (g_i A_{i\text{-}j} / U(T)) \, h\nu \, e^{-E_i/kT}$$

where n_0 is the particle density of the ground state of the particular species, g_i is the statistical weight of the upper state, $A_{i\text{-}j}$ is the transition probability for the particular emission from state i to state j, U(T) is the partition function, $h\nu$ is the energy of the emitted photon, E_i is

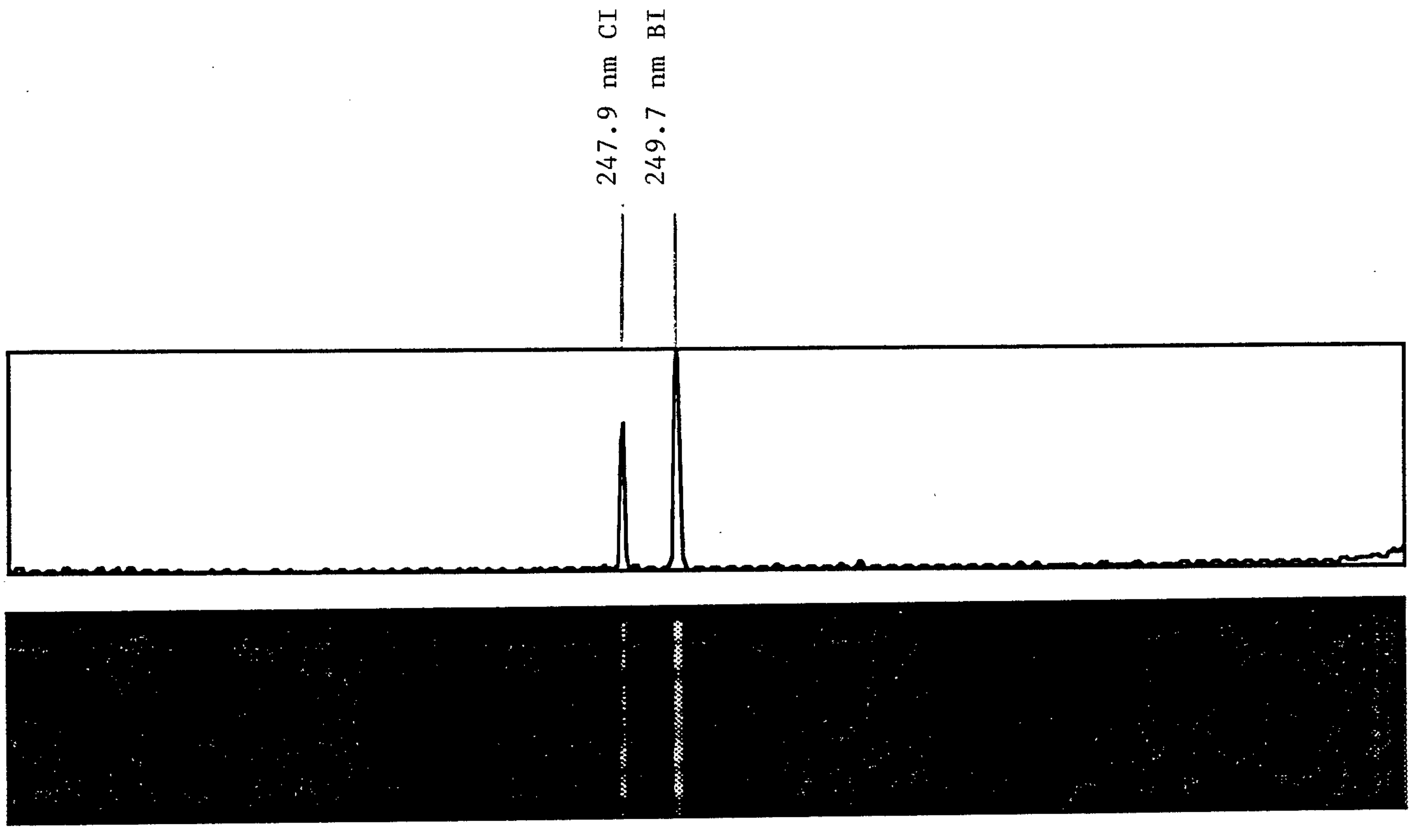

Figure 5a. Spectral Line Emission of Boron (249.7 nm) and Carbon (247.9 nm).

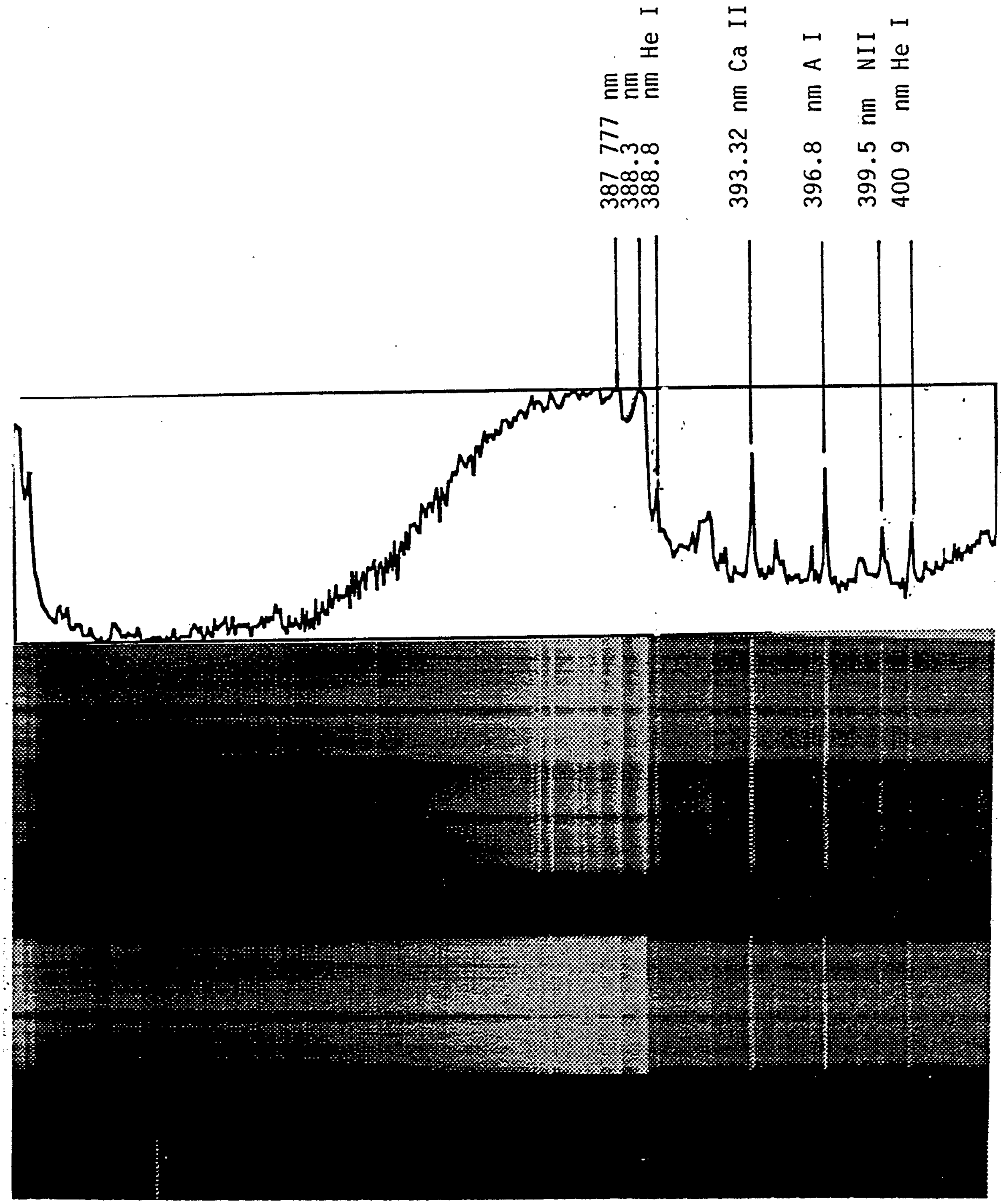

Figure 5.b Spectral Line Emission for Helium (388.8 nm and 400.9 nm analytical lines shown).

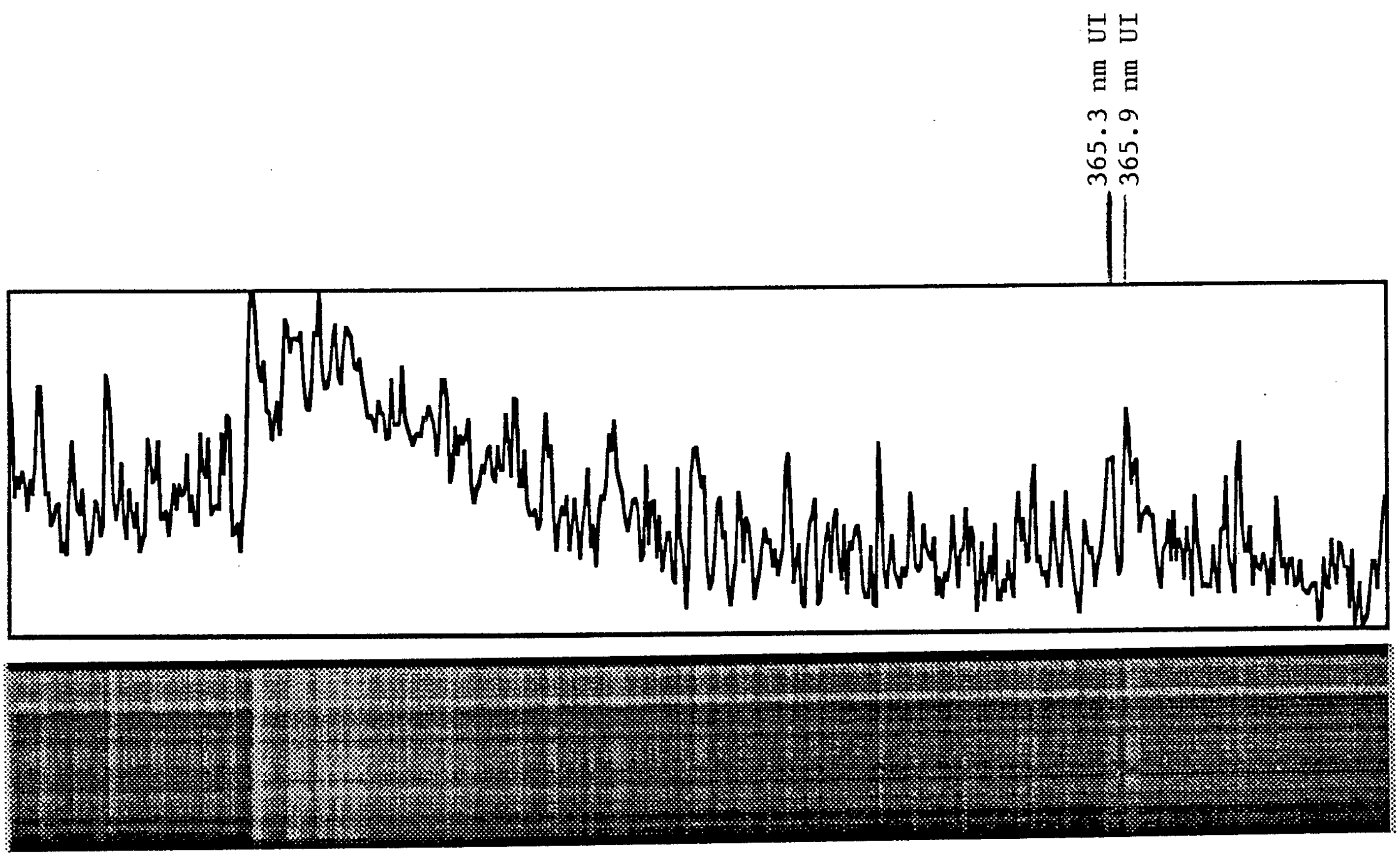

Figure 5c. Spectral Line Emission for Uranium (365.3 nm and 365.9 nm lines shown).

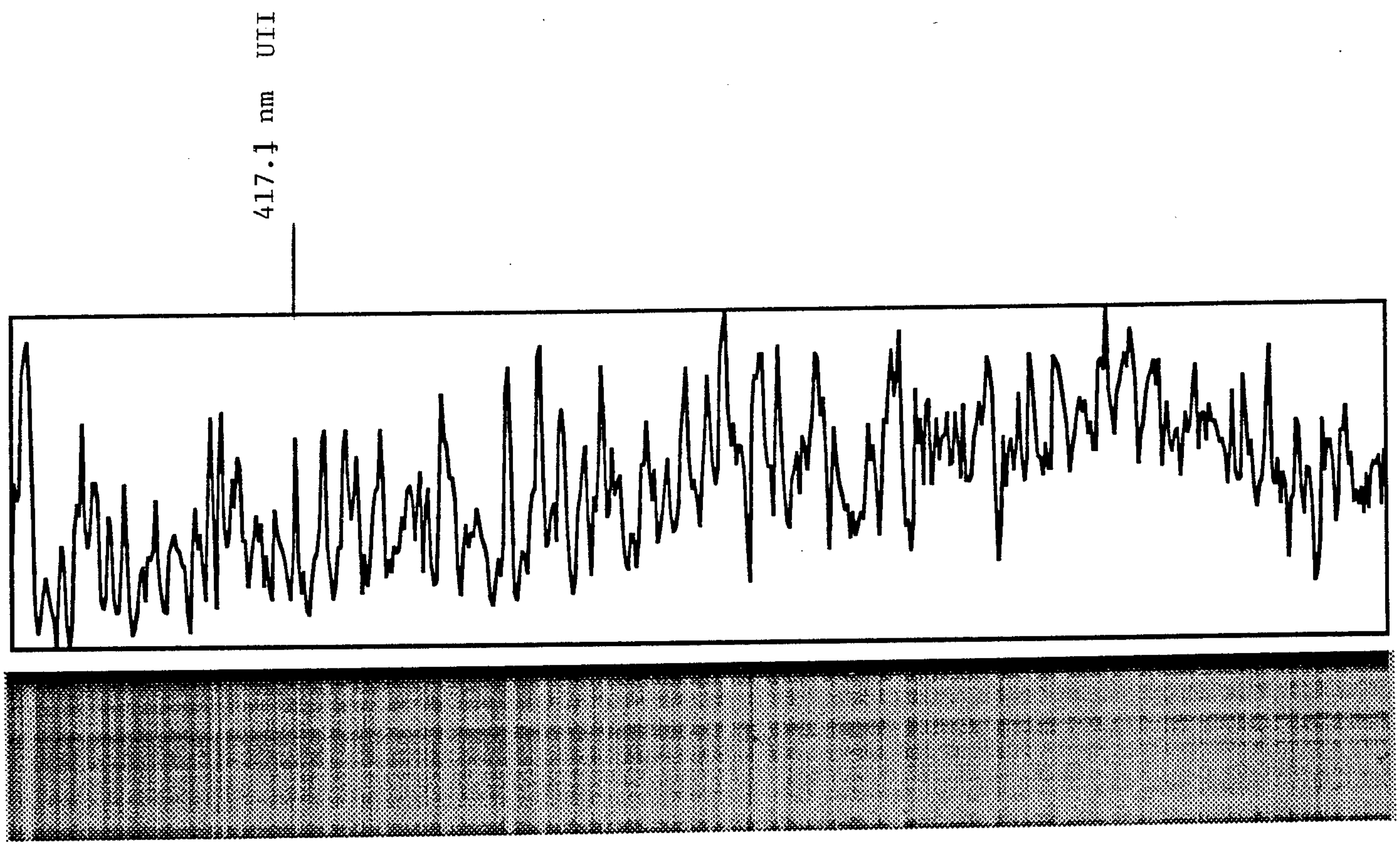

Figure 5d. Spectral Line Emission for Uranium (417.1 nm shown).

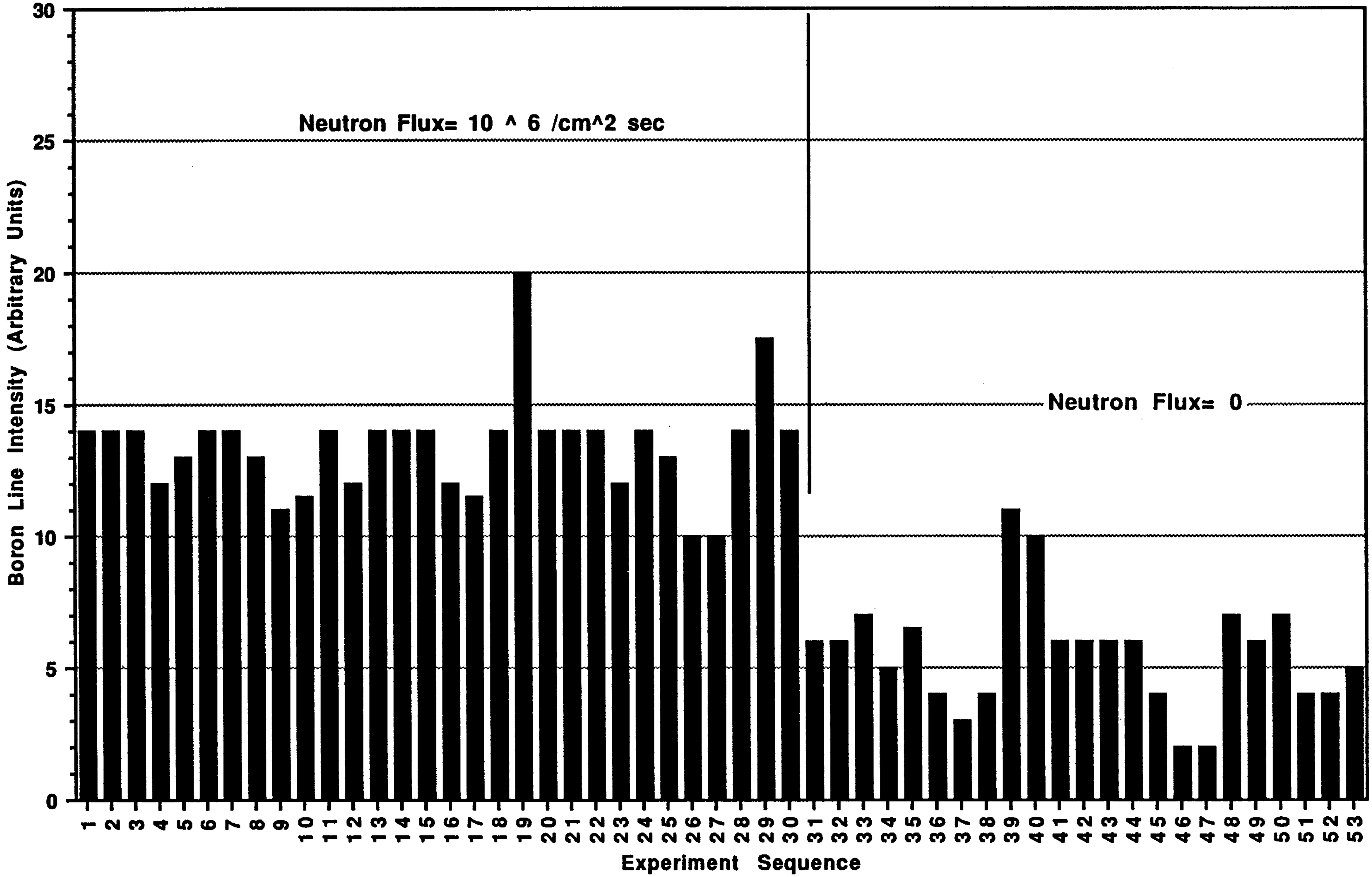

Figure 6.a Boron Doublet Line (249.77 nm) Intensity as Function of Neutron Irradiation

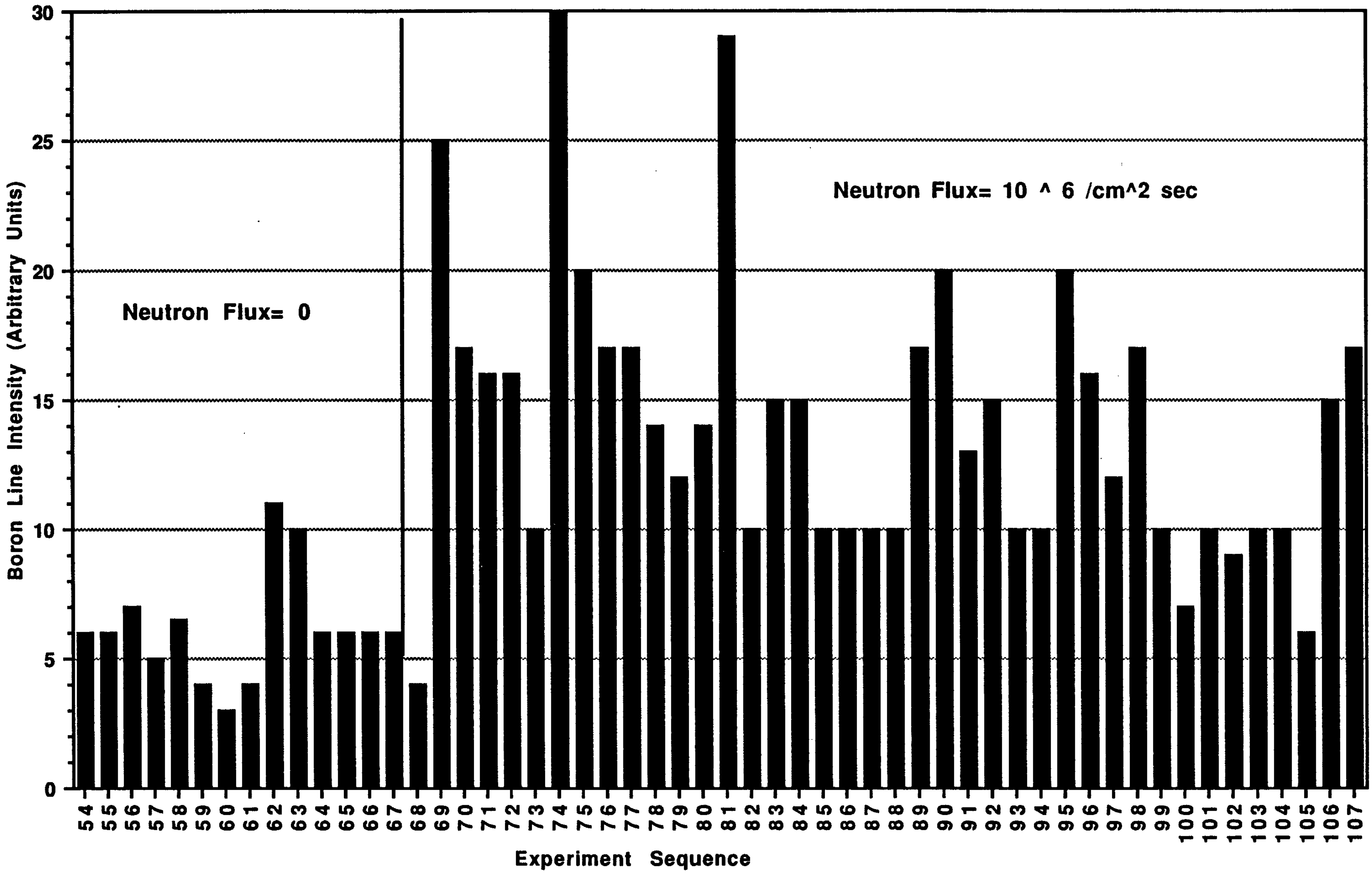

Figure 6.b Boron Doublet Line (249.77 nm) Intensity as a Function of Neutron Irradiation

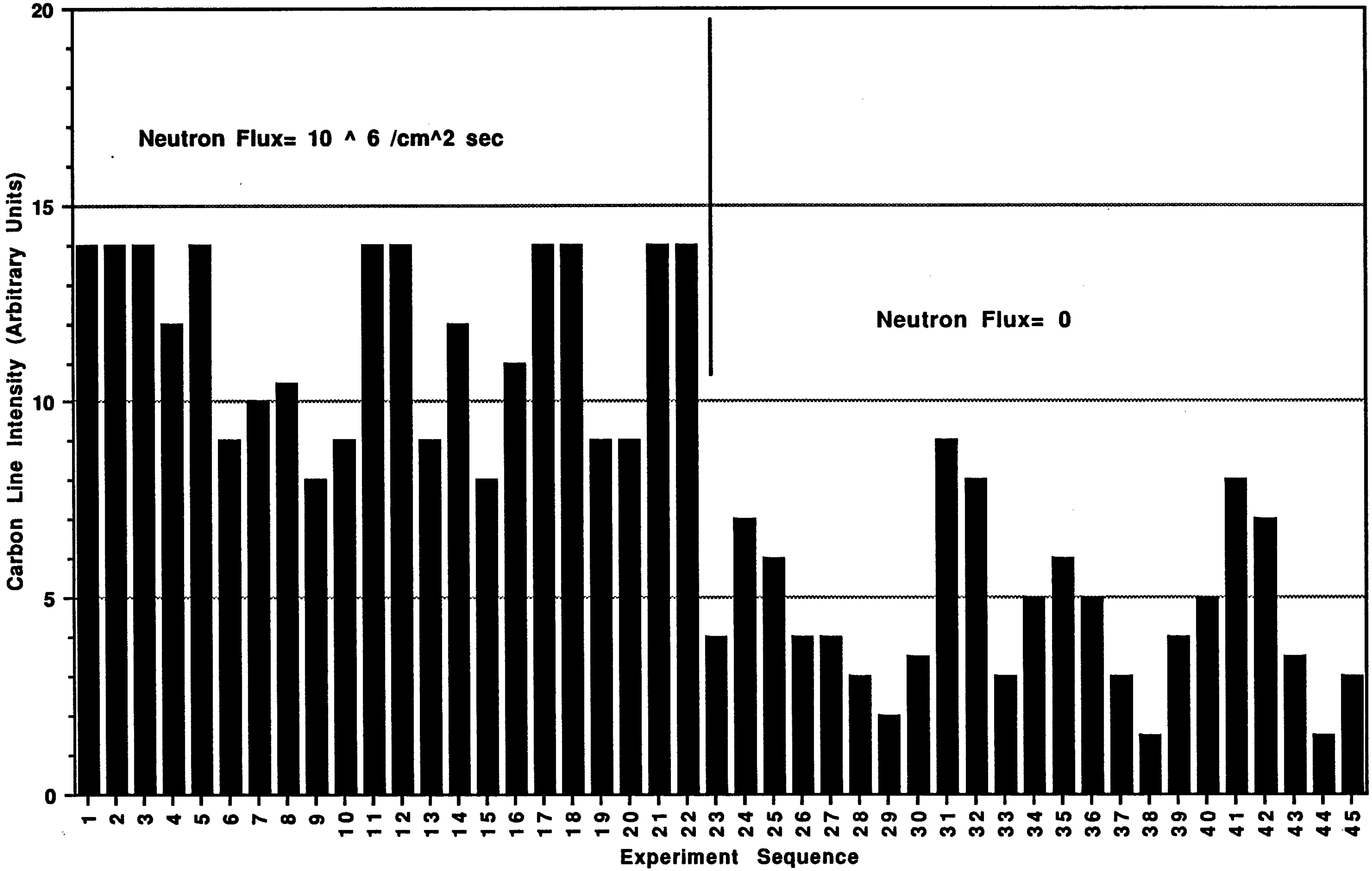

Figure 7.a Carbon Line (247.9 nm) Intensity as a Function of Neutron Irradiation

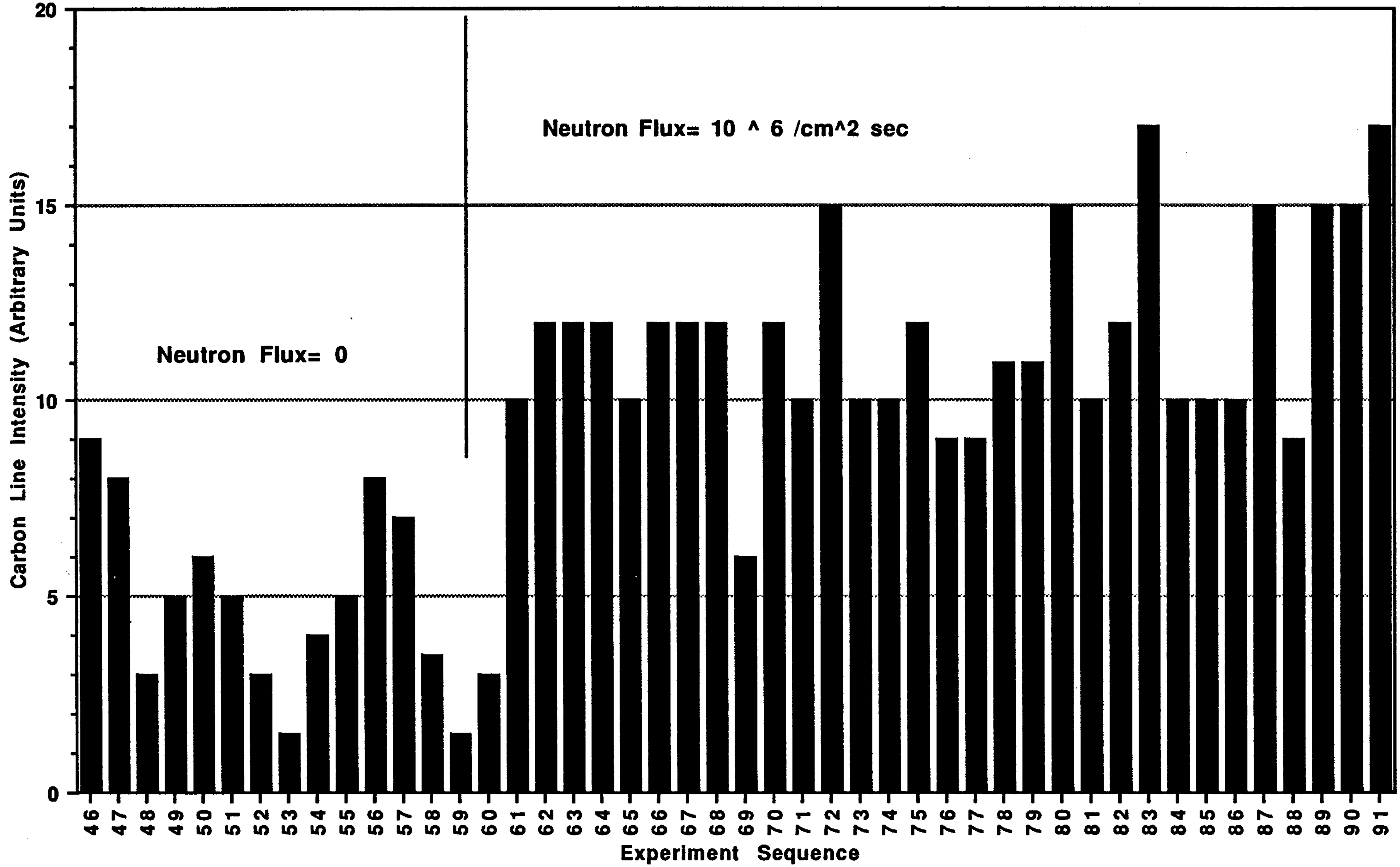

Figure 7.b Carbon Line (247.9 nm) Intensity as a Function of Neutron Irradiation

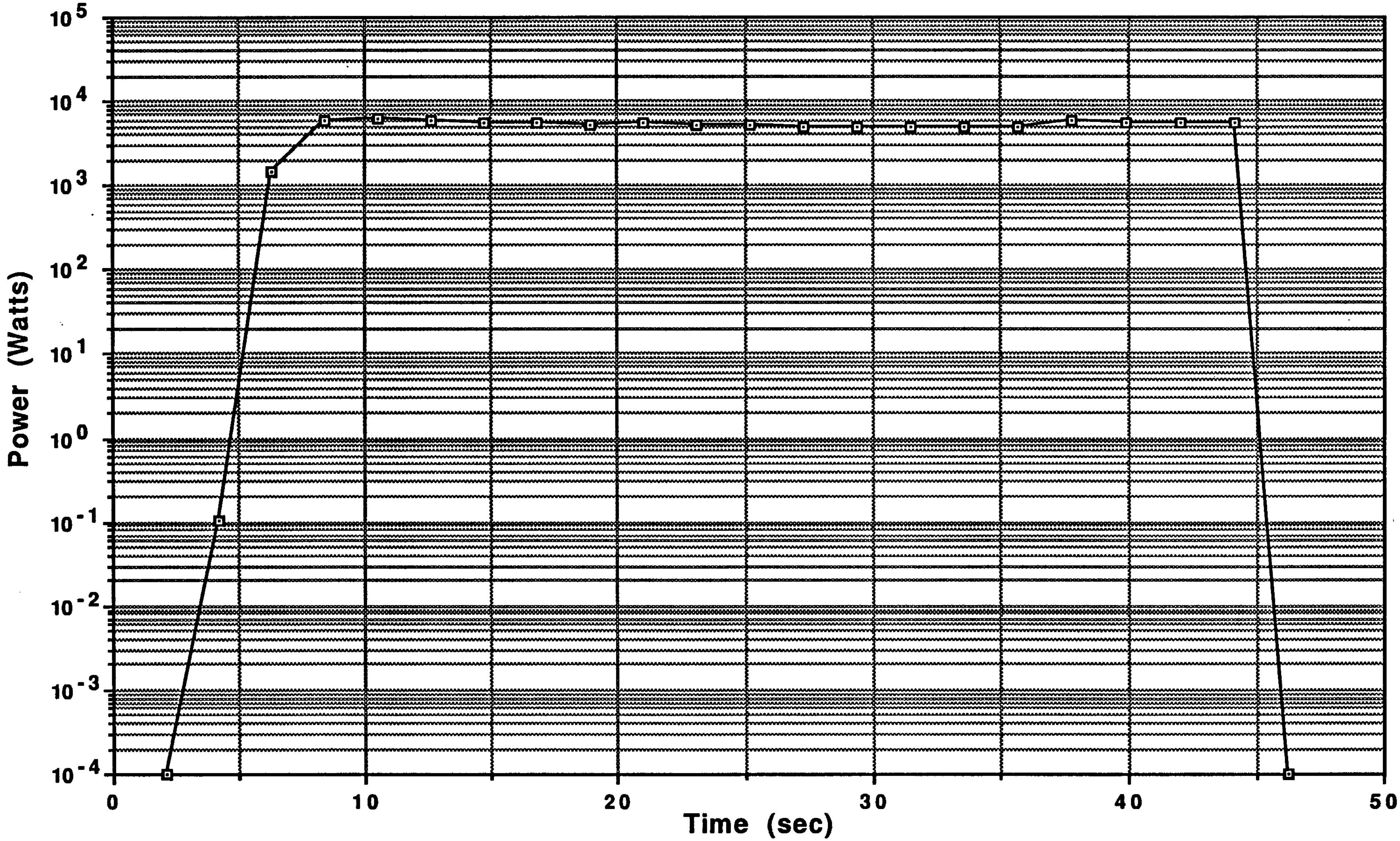

Figure 8. Measured Power Supply Input into Arc During Irradiation.

the energy level of the upper state, and I_i is the intensity density of the emitted line in (watts/cm^3). If one takes two lines from the same species, provided that their difference in excitation energies is large enough to produce the desired sensitivity, and provided that the lines are not self-absorbed, the ratio of the intensities of the two lines is given by:

$$\frac{I_2}{I_1} = \frac{\nu_2 g_2 A_{2-2'}}{\nu_1 g_1 A_{1-1'}} \exp\left(-\frac{E_2-E_1}{kT}\right)$$

from which a temperature can be derived.

The lines chosen for the temperature measurement were the 400.9 nm and the 388.8 nm helium lines. The graph showing the sensitivity of this line in the range between 5000 K and 20,000 K is shown in Figure 9. The temperatures during the boron test runs are shown in Figure 10, and the uranium run temperatures are shown in Figure 11. The results show that the boron arc temperature increased from ~9,500 K without irradiation, to ~11,500 K during irradiation with a neutron flux of 10^6 n/cm^2 sec. This is a 20% increase in plasma temperature. The uranium arc run temperatures increased from ~8,100 K to ~9,300 K, an increase of 15%.

The increase in arc temperature under the influence of neutron irradiation can be explained through an energy balance. An arc, as a rule is a self-sustaining discharge with a relatively low cathode fall potential (of the order of the ionization potential of atoms, about 10 eV). This small cathode fall results from cathode emission mechanisms that are capable of supplying a current which is indeed the total arc current. Arc cathodes emit electrons from processes such as thermionic, field, and thermionic field emission, etc. Arc cathodes use a large fraction of the electrical energy from the current to reach a sufficiently high temperature, either over the entire area or over a small localized area.

In principle, the cathode fall (or cathode layer), creates conditions for the self-sustainment of the current. The number of pairs of charges produced in the cathode layers of an arc is such that their reproduction is ensured by secondary emission due to thermionic influx. In the case of thermionic emission the electrons that are emitted create sufficient ionization to maintain a self-sustained discharge.

When the boron filled cathode is exposed to neutrons, fissioning of the boron atom produces two highly ionizing particles - He^4 and Li^7 with a positive Q value of 2.79 MeV. Uranium fission produces ionizing charged particles with a total kinetic energy of ~180 MeV. This energy is then used to ionize the plasma in the arc proper replacing the energy that once was needed to heat the cathode to produce electrons for arc self-maintenance. Since the power supply maintains a fixed current, as shown in Figure 8, the excess energy then goes

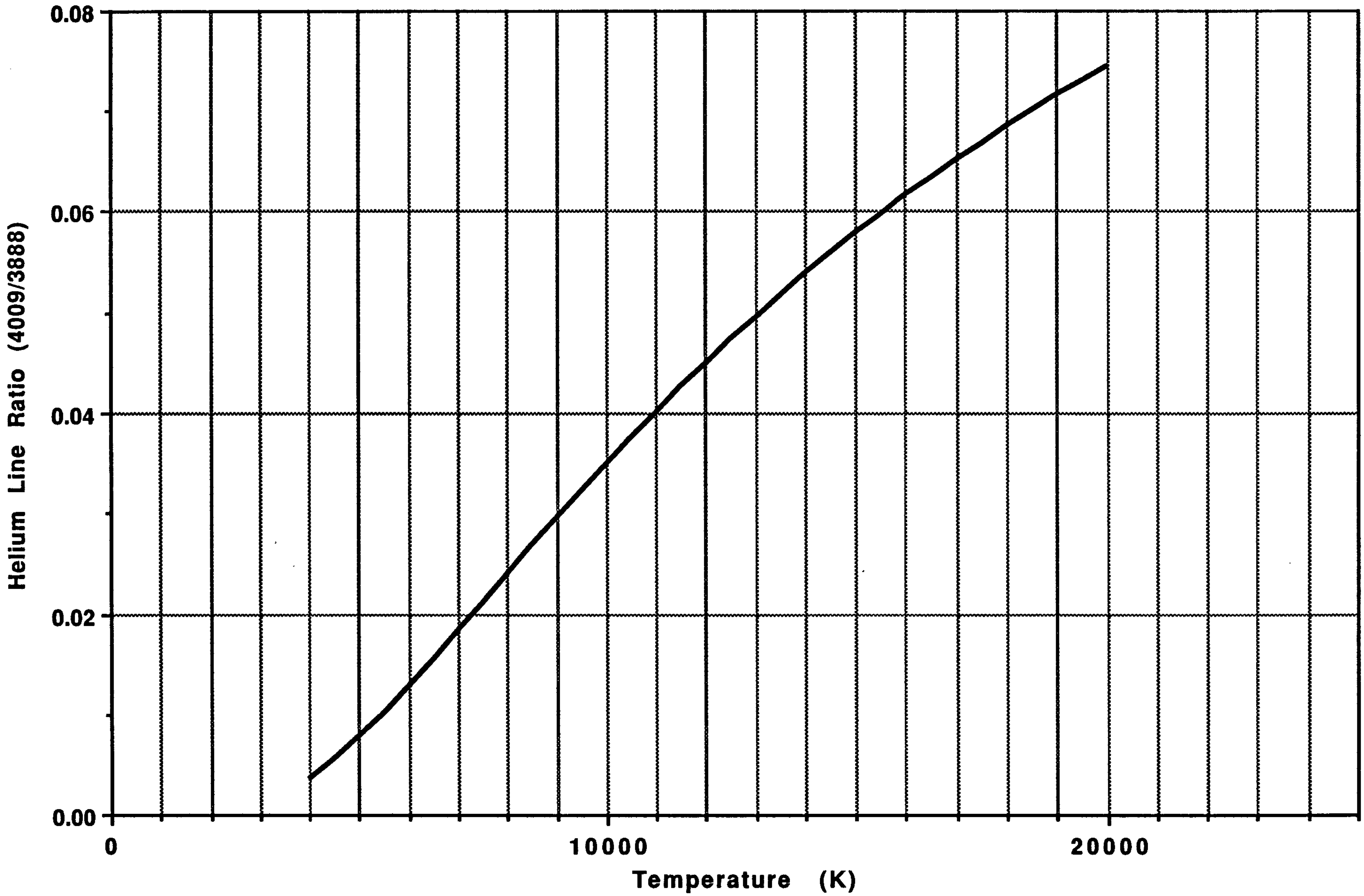

Figure 9. Line Intensity Ratio of Selected Helium Lines

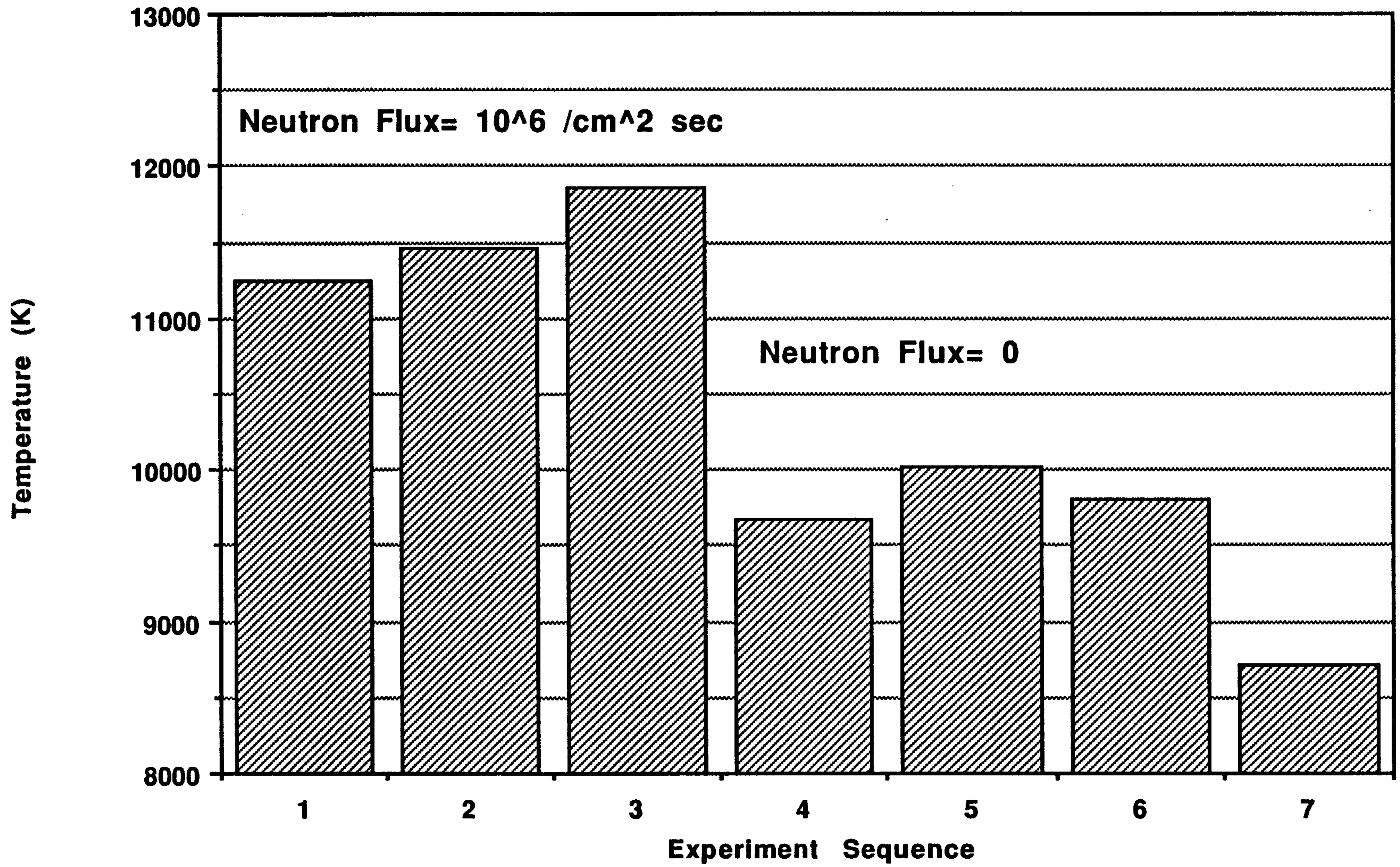

Figure 10. Nuclear Effect on Boron Arc Plasma Temperature

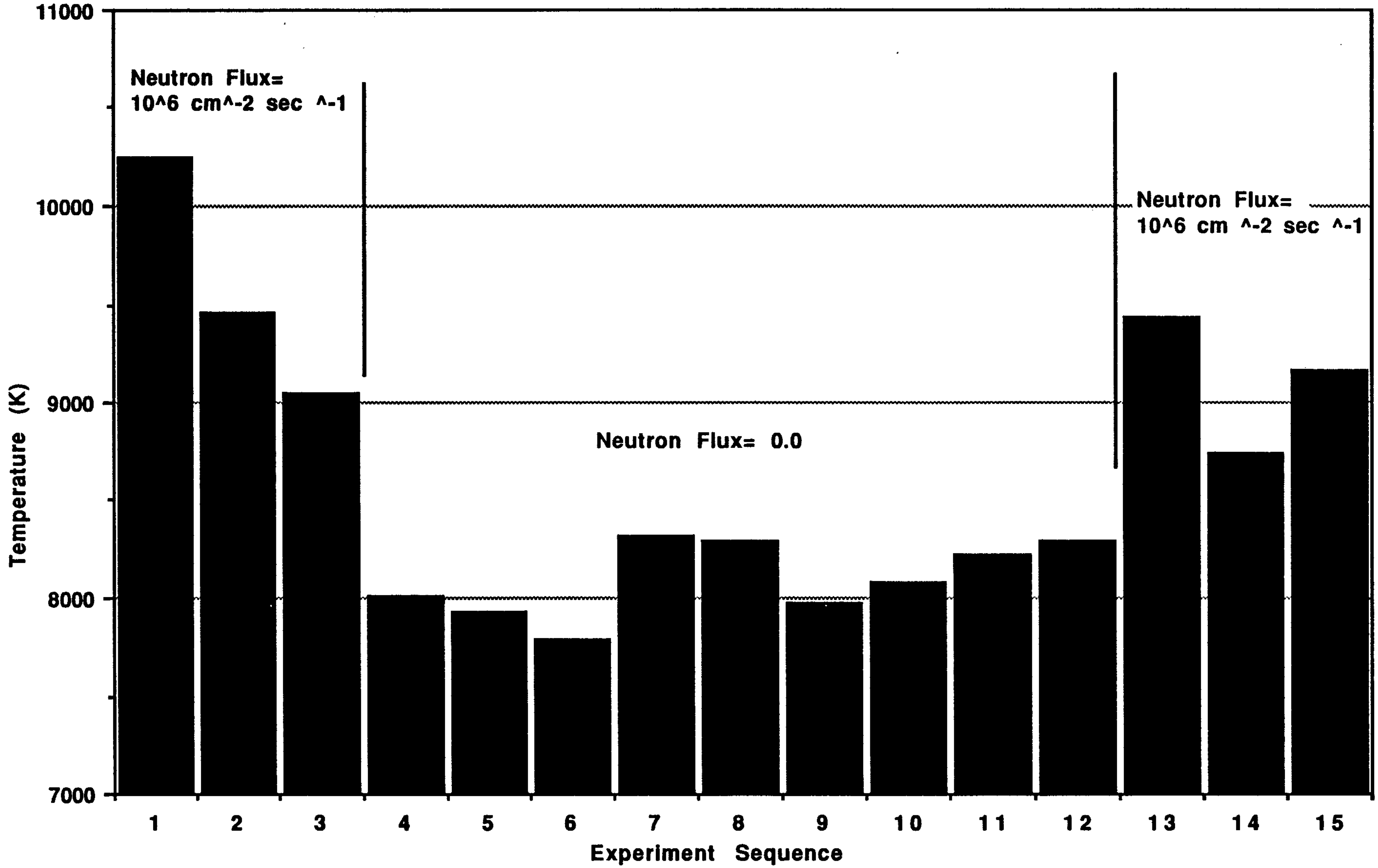

Figure 11. Nuclear Effect on Uranium Arc Plasma Temperature

into heating and thus raising the temperature of the plasma. Thus, both the uranium, boron and carbon line intensities were observed to increase correspondingly.

The uranium atom and ion densities can be obtained from the measured line intensities, the helium line ratio temperature measurements, and the above equations. These values can be compared to the densities obtained by assuming thermal equilibrium and using Saha equations. This methodology is described in Reference 7. The results are shown in Figure 12. The calculated densities for the uranium arc runs without irradiation, based on the measured line intensities, are shown as the data points with the appropriate error bars. The curves represent the results of Saha equilibrium calculations for the range of uranium pressures during the experiments. The results show that the data lie in the region bracketed by the Saha curves. This provides a good benchmark check of the measurements and calculational methodologies.

4.3 Electrical Conductivity

Figure 13 shows the VI characteristics for uranium arcs with and without neutron irradiation. The VI curve without irradiation is comparable to that obtained in Reference 9. The operating conditions such as pressure and helium flow rates were the same for experiments with and without irradiation. Figure 13 shows that for a given voltage, a fissioning plasma will support a larger current. This is equivalent to a decrease in the plasma resistance, i.e., an increase in the conductivity, and is consistent with the general findings in References 1 and 2. The temperature in the current experiments was ~8,000 K, compared to ~2,500 K in References 1 and 2. Thus, the fractional increase can be expected to be lower in the current experiments.

The measured uranium arc conductivities derived from VI characteristics are shown in Figure 14. For a given plasma conductivity, a fissioning plasma can support more power because it can more efficiently couple it into the arc and thus radiate it away. At a given power level however, a fissioning plasma will require a significantly lower temperature to balance electrical power input and radiated power output. Due to the lower temperature at a given power level, its conductivity will be correspondingly lower.

4.4 Radiative Energy Absorption and Mass Transfer

To achieve ultrahigh temperatures, optically thin propellants such as hydrogen will need to be seeded with material which will absorb and transfer arc-emitted radiation. For this reason, the next series of experiments were performed to investigate if the optical radiation emitted by the arc plasma could be absorbed and thus used to increase the propellant temperature.

To accomplish this, the same experimental setup was used as described above, the arc operated with uranium, and total radiation intensity passing through a test cell was measured with a radiometer. The radiometer measures the total spectrum of light incident on its

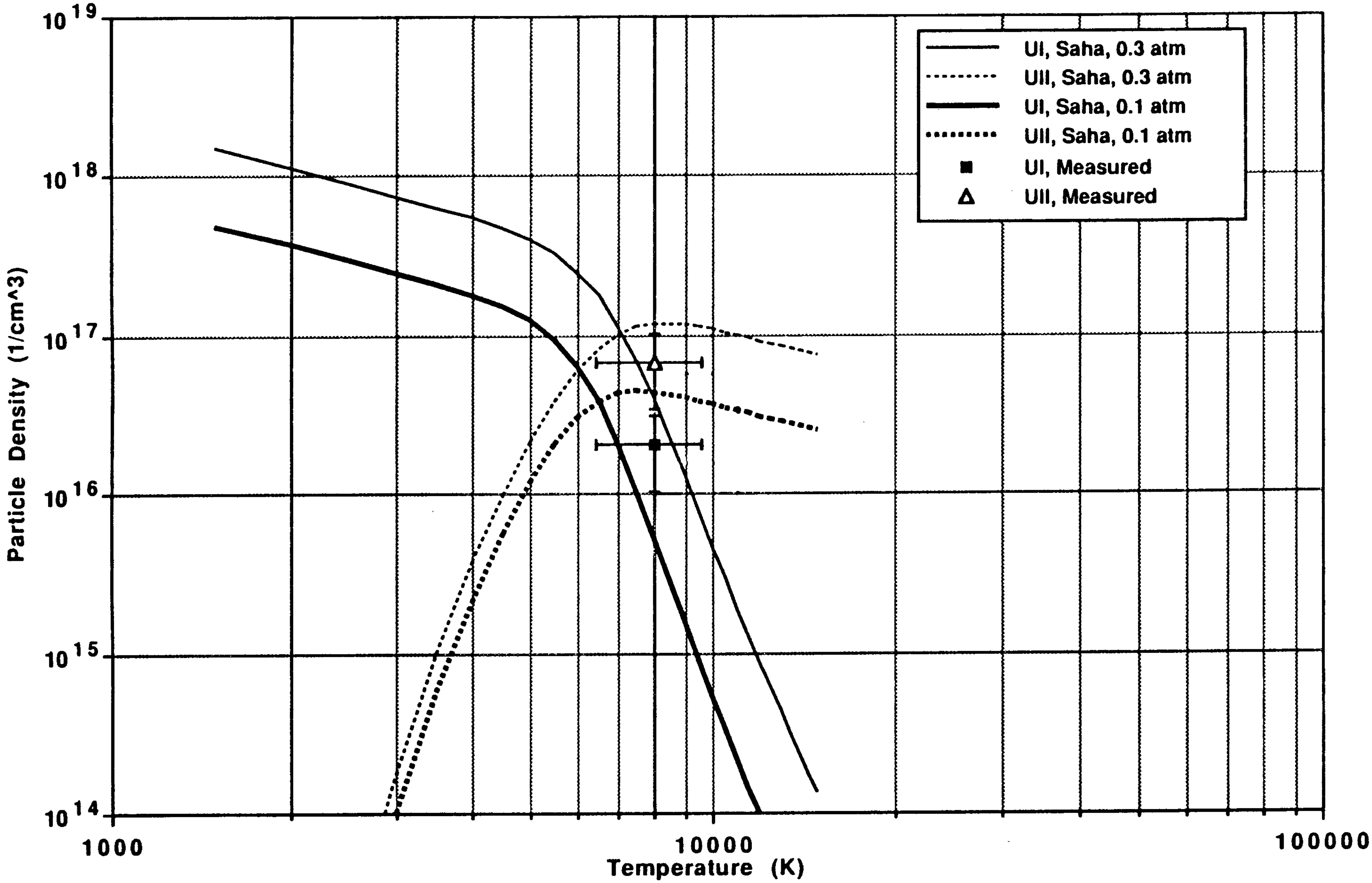

Figure 12. Equilibrium Particle Density Population. Uranium Total Pressures: 0.1,0.3 atm

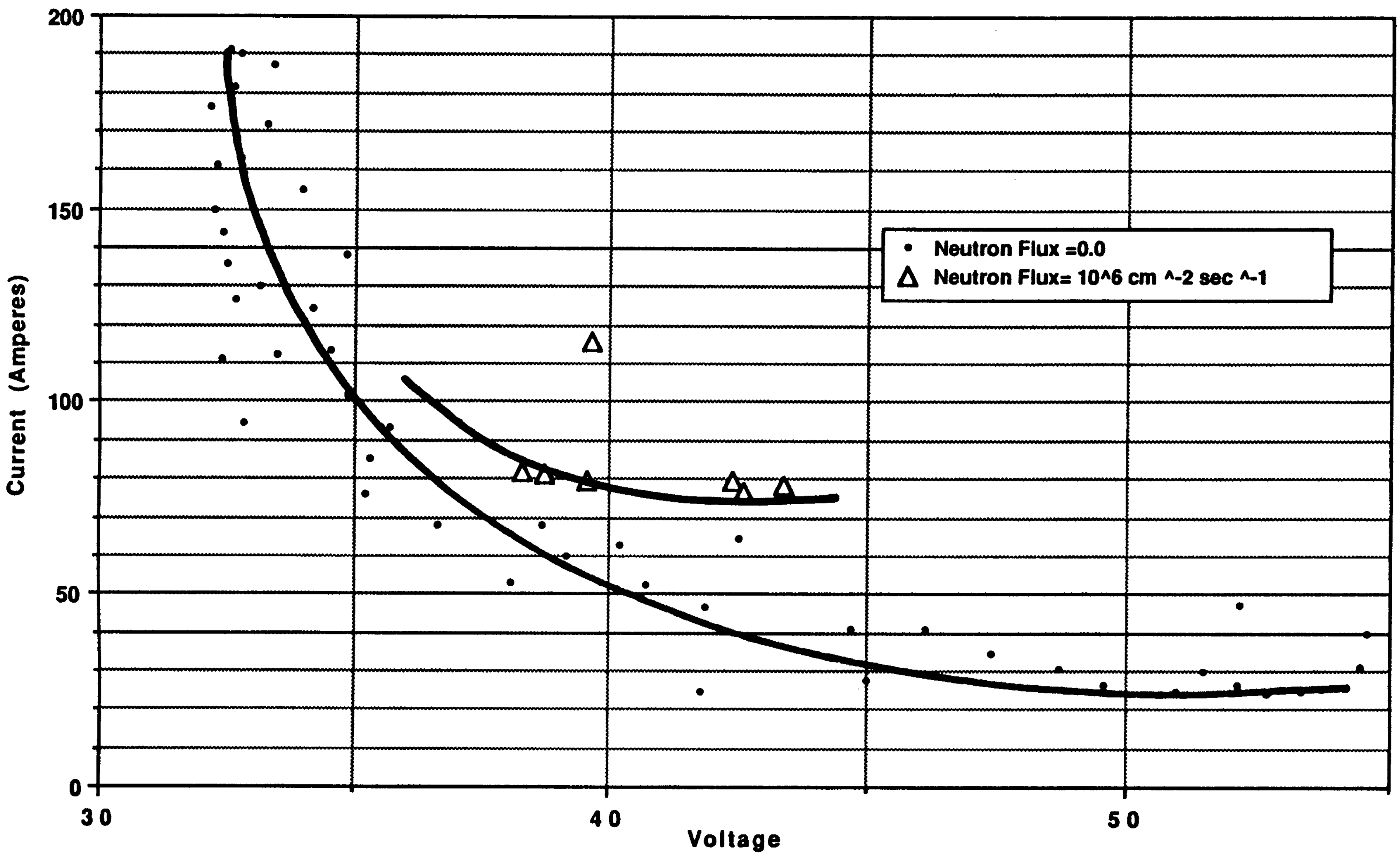

Figure 13. Uranium Arc V-I Characteristic Curve

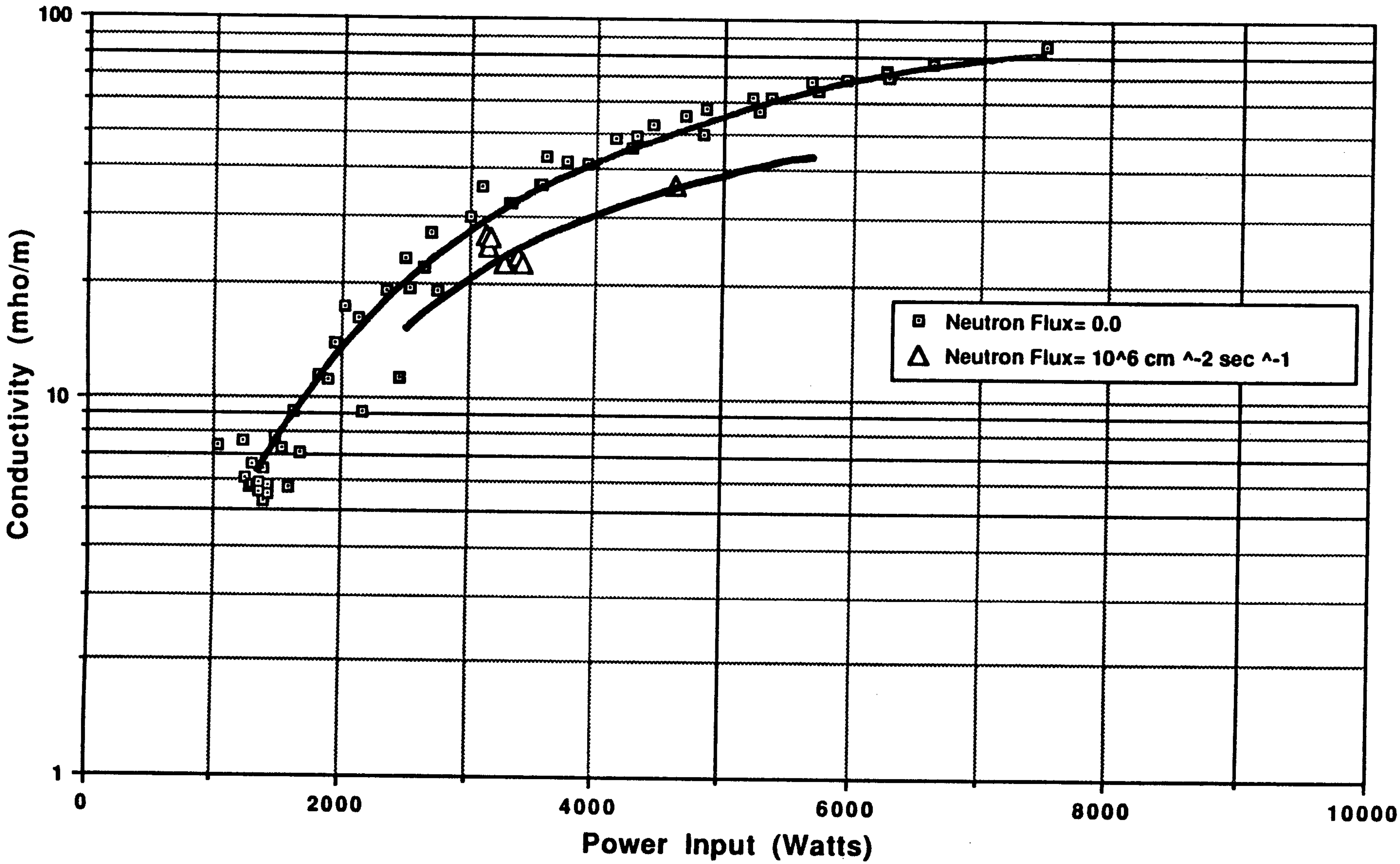

Figure 14. Electrical Conductivity of Uranium Arc Plasma

photocell, in contrast to the single line spectrometer measurements described above. To simulate the maximum absorption potential of seed material, a UF_6 absorption test cell was placed between the arc and the radiometer, and the uranium partial pressure in the test cell was varied.

The results of the transmissivity measurements with varying UF_6 particle pressure in the absorption cell are shown in Figure 15. The UF_6 particle density in the absorption cell was obtained by monitoring the temperature and pressure in the reservoir. The temperature was maintained in the range of 350 K to 360 K, while the UF_6 pressure was increased from vacuum (1-2 torr) to 1 atm. The figure shows an inverse dependence of transmissivity on the UF_6 particle density. At a particle density of 2×10^{19} cm^{-3} (1 atm and 360 K) and an optical path length of 10 cm, the UF_6 absorbed 90% of the emitted light.

One of the key aspects of the uranium arc fission reactor is the ability to minimize fuel loss from the reactor via the electric field confinement. Data from the uranium mass flow rate experiments are presented in Figure 16. The experiments were performed for a range of currents from 20 to 30 amp. In addition, the physical configuration of the uranium within the cathode pin was also examined. Thus, the uranium was inserted at various depths into the pin to examine the impact on fuel loss rate. Due to limitations in the scope of the effort, optimization of operating parameters could not be performed. However, Figure 16 indicates that the mass loss rate from the electrode can be decreased to very low levels (few mg/cm^2s), by proper electrode design.

Uranium recirculation and recovery was also performed by operating the uranium pin as the cathode. In these experiments, uranium atoms evaporating from the pool surface are returned to the pool by the effect of the electric field. Uranium loss from the electrodes could thus condense on cold surfaces near the electrode within the arc assembly. Thus, uranium either exhausted with the helium, or was recovered within the arc assembly. The results of these experiments are shown in Table 1. The results show that up to 50% of the lost uranium can be recovered in this manner.

Table 1. Summary Uranium Recirculation and Recovery Experiments.

	Experiment # 1	Experiment # 2
Average Insertion Distance (mm)	0.0	1.0
Total Loss (grs)	0.220(100%)	0.391(100%)
Losses through Helium Flow (grs)	0.193(88%)	0.179(46%)
Recirculated Uranium Recovered (grs)	0.026(12%)	0.211(54%)

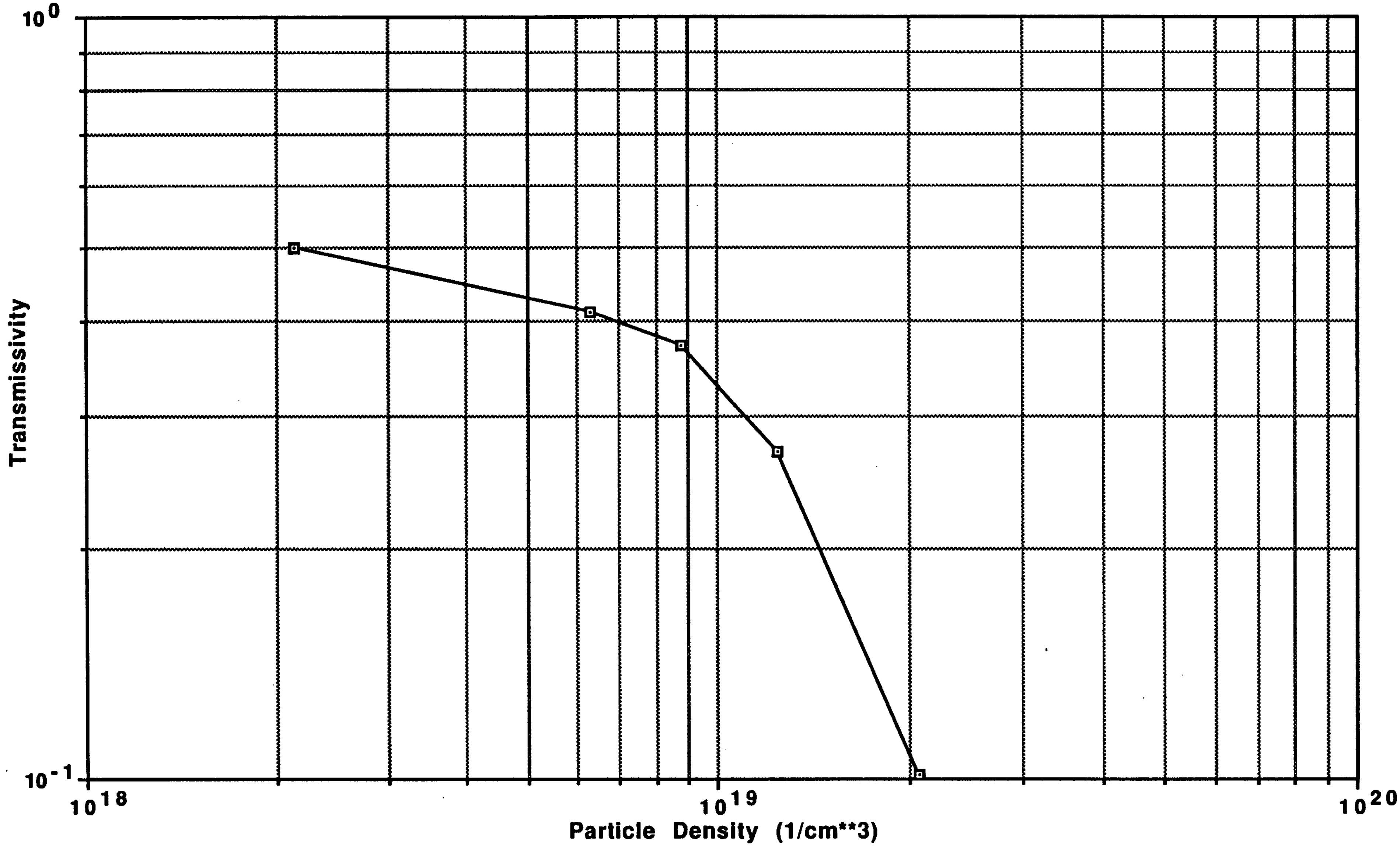

Figure 15. UF6 Transmissivity vs Particle Density

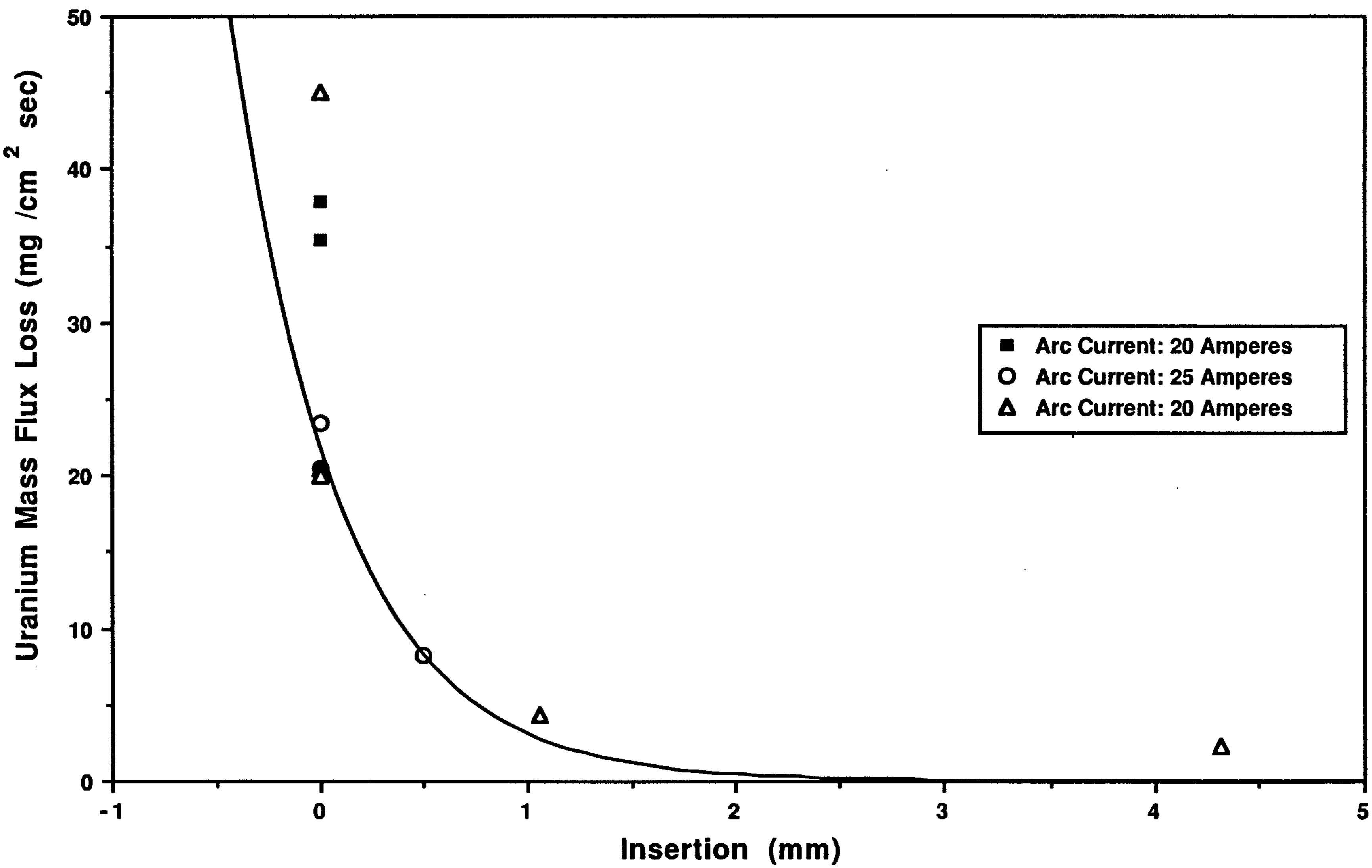

Figure 16. Gravimetric Measurements of Uranium Loss vs. Insertion Distance and Arc Current

5. CONCLUSIONS

The basic parameters supporting the Uranium Arc Fission Reactor (UAFR) concept were measured with encouraging results. This new concept for nuclear space power and propulsion boosts propellant exhaust temperatures via rapid radiative energy transfer at ultrahigh temperatures without requiring solid heat transfer surfaces.

A new effect was observed supporting the transfer of energy into an arc plasma. In this effect, the line intensity emitted by an arc plasma containing or supported by fissile material was increased by neutron irradiation. A preliminary explanation is that this is interpreted as a plasma temperature rise by the more efficient ionization mechanism provided by the fast, charged fission fragments. The spectroscopically measured temperature increased from 8,100 K to 9,400 K (15%) with uranium arcs, and from 9,500 K to 11,500 K (20%) with boron arcs.

This new effect was observed at surprisingly low neutron fluxes. The results are unexpected because the nuclear energy released does not explain the calculated enthalpy rise of the plasma. Though a detailed explanation has not been developed, the effect potentially results from the high ionization efficiency of high energy charged particles compared to electric field/ohmic heating, thus allowing more efficient use of the electrical energy available to the arc for raising plasma temperature. This effect can be applied in electric thrusters to reduce the electrical power requirements needed for ionization of the propellant. The research effort yielded new insight into the interaction of MeV fission fragments with eV plasmas. The next level of research will need higher fluxes and more detailed measurements to establish a theoretical basis.

The optical radiation emitted by the arc plasma can be absorbed by an external medium. At a particle density of 2×10^{19} cm^{-3} (1 atm and 360 K) and an optical path length of 10 cm, 90% of the emitted light can be absorbed. Mass loss rates from the electrodes can be reduced to a few mg/cm^2s, a large fraction of which can furthermore be recovered.

The experimental results indicate the fundamental feasibility of uranium arc driven energy transfer. For thermal propulsion, increased temperatures mean higher specific impulse thrust. For space power platforms, the resultant improved efficiency means reduced and easier waste heat rejection and thus a more compact, lower mass reactor design. A more efficient thruster also results in lower power requirements or reduced radiator area and thus mass. The technology is also applicable for more efficient and safer ground-based electric power generation. A spinoff development is the technology for handling uranium and its compounds in liquid and vapor forms. This technology will be required in advanced Gas and Vapor Core Reactors.

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